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Bulletin volcanologique

ORGANE DE

l'Association de Volcanologie

de l'Union géodésique et géophysique internationale

Publié par le Secrétaire général

† FRANCESCO SIGNORE

Série II — Tome XXII

Comptes rendus
de la XI^e Assemblée Générale à Toronto
3 - 14 Septembre 1957
III^e Partie

B. V.

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GORDON A. MACDONALD *

The activity of Hawaiian volcanoes during the years 1951-1956

(With 17 figures and 20 plates)

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Introduction

During the decade 1940-1950 Hawaiian volcanic activity was restricted wholly to Mauna Loa (MACDONALD, 1954). Early in the present decade, however, activity shifted to Kilauea, leaving Mauna Loa quiescent. Eruptions in Kilauea caldera

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* Volcanologist, Hawaii Institute of Geophysics. Publication authorized by the Director, U. S. Geological Survey, Hawaii Institute of Geophysics Contribution No. 14.

in 1952 and 1954 were followed in 1955 by a flank eruption 32 kilometers east of the caldera. Thus the pattern at Kilauea during the first five years of the decade resembled the succession of summit eruption followed by flank eruption commonly observed on Mauna Loa.

The return of activity to Kilauea did not bring a resumption of the quasi-permanent lava lake activity long considered characteristic of that volcano. Through the first century during which the volcano was known to Europeans (1823-1924) an active lava lake was present in the caldera a large proportion of the time. However, the lake disappeared during the collapse and accompanying steam explosions in 1924 (see next chapter), and has been reestablished only for brief intervals during more recent eruptions. Not only has the continuous lava lake activity not reappeared, but the eruptions of recent years have been characterized by much larger primary lava fountains than those of the earlier « typical » Kilauean activity. No doubt the two differences are closely related. The continuous lava lake during the years previous to 1924 indicated a magma-filled conduit open to the surface, within which the accumulation of any large « head » of gas was impossible, and which consequently could not give rise to such large gas-rich fountains as have characterized the eruptions of Mauna Loa and the recent eruptions of Kilauea.

There appear to be no good grounds for assuming that the type of activity that characterized Kilauea during its first century of observation has been characteristic of the entire history of the volcano. On the contrary, the geologic structure of the volcano suggests that its activity has more generally resembled that of Mauna Loa, with frequent flank eruptions interspersed with short periods of summit activity. Thus the change in character of activity since 1924 may be a return to normal in the long-term history of the volcano.

The form and structure of Kilauea volcano have been described elsewhere (Stearns and Macdonald, 1946, pp. 99-110, 129-131; Macdonald, 1955, pp. 24-25; 1956, pp. 274-287). Briefly, Kilauea is a broad shield volcano, built against the

southeastern slope of the larger Mauna Loa (fig. 1). At its summit is a caldera 4 kilometers long, 3.2 kilometers wide, and 120 meters deep. Within the caldera, southwest of its center, lies the crater of Halemaumau, which for the past century has been the principal site of activity of the volcano. Extending southwestward and eastward from the caldera are two rift zones, along which most of the flank eruptions have taken place. The 1955 eruption, described in later pages, occurred on the east rift zone. Along the southern edge of the shield the Hilina fault system (STEARNS and MACDONALD, 1946, p. 40) is a series of high-angle faults, nearly parallel to the rift zones, along which the summit portion of the shield has been elevated relative to the portion below sea level to the south. Another series of faults, the Kaoiki fault system, lies west and northwest of the caldera at the junction of Kilauea and Mauna Loa. Evidence suggests that this fault system acts as an adjustment plane on which slippage occurs during tumescence or detumescence of either volcano.

Local Seismicity

In the following text repeated reference is made to *local seismicity*. This is an arbitrary value, which for many years has been used at the Hawaiian Volcano Observatory as a measure of the number and strength of earthquakes emanating principally from Kilauea and Mauna Loa volcanoes. It is derived by assigning a numerical value to each earthquake, according to the size of the maximum double amplitude of the oscillation it produces on a seismogram. The standard instrument for this purpose has been the Bosch-Omori horizontal pendulum seismograph, with a static magnification of 115 and a period of 7.7 seconds, in the Whitney Laboratory of Seismology at the northeastern rim of Kilauea caldera (fig. 10). For example, a very feeble earthquake, with a double amplitude on the seismogram of 0.5 to 4 mm, is assigned a seismicity value of 0.5; whereas a moderate earthquake, with a double amplitude of 25 to 60 mm, is assigned a value of 3.0. The values for individual earthquakes are then totalled to

derive the local seismicity for any given period, commonly one week. The value is no more than a very rough semi-quantitative measure of the amount of energy actually released by earthquakes during the period in question, but it has served to indicate in a general way the variations in seismic activity.

In recent years the old seismographs on the island of Hawaii have been gradually replaced with modern and much more sensitive instruments; and the local seismicity, as defined above, is being replaced by a more precise value, known as the strain-release index, based on the actual amount of energy released by each earthquake in a given region (J. P. Eaton, in Macdonald and Eaton, 1957, p. 32-34).

Brief history of activity of Kilauea

Kilauea was first visited by Europeans in 1823. Prior to that, knowledge of the volcano's activity is based wholly on rather vague native tradition. The eruption of large areas of fresh-appearing pahoehoe flows in the area west of Pahoa (fig. 1) probably is reflected in tales of the inundation by lava of large parts of the eastern (Puna) district of the island during the reign of an early chief, Keliikuku, presumably since 1000 A. D. Another eruption apparently took place about 1350 A. D., at the cone known as Kaholua o Kahawali, 7 kilometers east of Pahoa (Macdonald, 1941, p. 1). Other flows occurred on the east rift zone about 1750 and 1790. The positions of these flows are shown in figures 1 and 12.

During the 19th Century the history of Kilauea caldera was one of repeated collapses and refillings. The somewhat conflicting accounts of the form of the caldera have been analyzed by Finch (1940, 1941), and the following brief account is taken from his papers and the histories of the Hawaiian volcanoes by Dana (1890), Brigham (1909), and Hitchcock (1909).

The first European to visit Kilauea caldera was William Ellis, an English missionary. He reports (Ellis, 1827, p. 177) that during early August, 1823, the caldera consisted of an inner pit with its floor about 300 meters below the western

rim of the caldera, surrounded by a « black ledge » about 200 meters below the rim (60 to 90 meters below the present

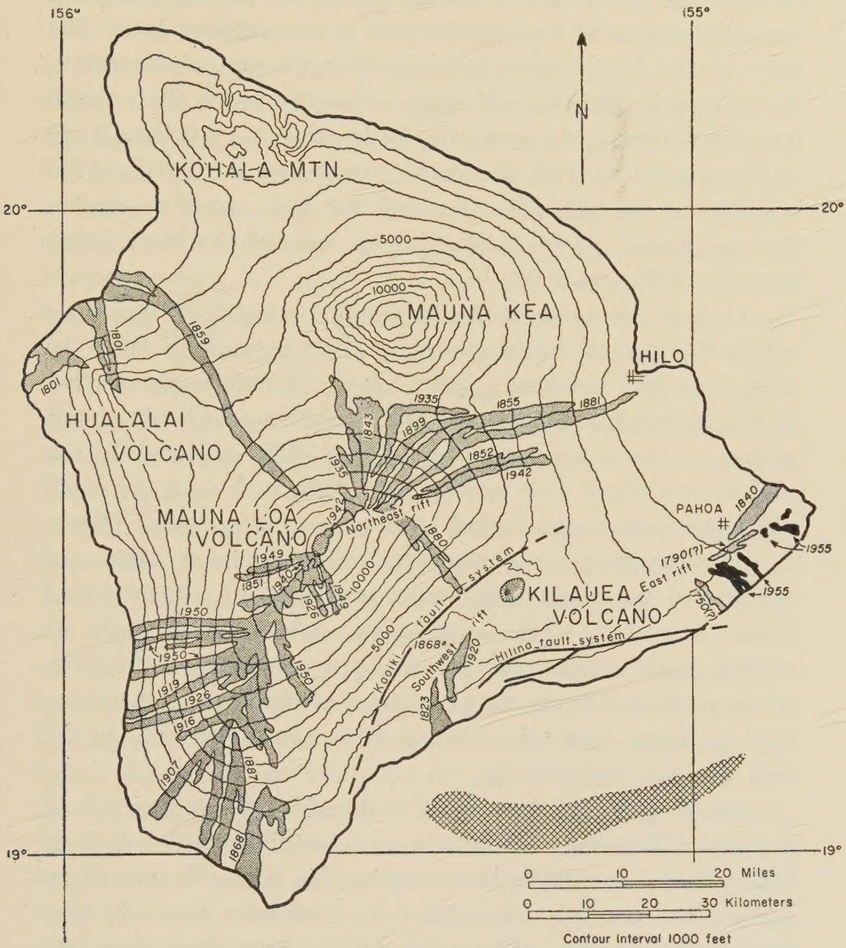

Fig. 1 - Map of the island of Hawaii, showing the lava flows of 1955 (solid black) and earlier historic flows (stippled). The cross-hatched area south of the island is the zone in which the great earthquake swarm of March and April, 1952, originated.

caldera floor). This « black ledge » or bench encircling the inner pit was a common feature in early descriptions. The inner pit occupied most of the area of the caldera, and was

the site of eruptive activity, apparently at least in part of lava lake character. Only a few months previously an outflow of lava had taken place on the southwest rift zone (fig. 1), and the sinking of the central part of the caldera below the level of the black ledge probably was the result of removal of support by drainage of magma from beneath the caldera into the rift zone. It is generally believed that a similar sinking of the central part of the caldera occurred during the 1790 eruption on the east rift zone, and that the central depression thus produced had been filled to the level of the black ledge between 1790 and 1823.

During the years immediately following 1823 eruptions within the central basin gradually filled it, and by 1832 the new floor had reached a level about 15 meters above that of the former black ledge. Another subsidence of the central portion of the caldera occurred during 1832, and in 1834 the caldera was much as it had been in 1823, with an inner basin 120 meters deep surrounded by a narrow black ledge. Again in the succeeding years eruptions filled the inner basin and overflowed the black ledge with new lava. By 1840 a broad dome 30 meters high occupied the caldera floor, with its summit in the southwestern part of the caldera in the vicinity of the present Halemaumau. A crater at the apex of the dome held an active lava lake. During late May the activity in the lake was unusually strong.

On May 30, 1840, a small outbreak of lava occurred on the east rift zone 10 kilometers east-southeast of the caldera, followed by several others within the next 10 kilometers further east, and two days later by outbreaks 30 to 40 kilometers east of the caldera that sent a large lava flow into the ocean (figs. 1 and 12).

The flank flow of 1840 was accompanied by another collapse of the central portion of the caldera, but the area of the central basin was smaller than in 1823 and 1832. As mapped by the U. S. Exploring Expedition in 1840, the inner pit was 105 meters deep and oval in outline, with a long diameter of approximately 2.9 kilometers and an average

shorter diameter of 1.6 kilometers. The black ledge around it averaged 480 meters in width, and stood at an average level about 200 meters below the western rim of the caldera. By 1846 the inner basin was again filled to and above the level of the black ledge. The filling was partly by flows over the floor of the basin, but also partly by a bodily elevation of the floor. This elevation brought up not only the relatively flat lava floor of the basin, but also the taluses that had accumulated at the foot of the cliffs enclosing the basin, producing a narrow ridge of fragmental debris more than 1.6 kilometers long that stood 15 to 30 meters above the adjacent caldera floor. During 1848 a dome 1,000 meters across and 60 to 90 meters high was built, with its apex in the southwestern part of the caldera. From 1838 on, and probably earlier, the principal center of activity in the caldera was near its southwestern edge, at or near the site of the present Halemaumau.

Early in April, 1868, a small flank eruption took place on the southwest rift zone, accompanied by still another collapse in the caldera. An area approximately the same as that of the inner basin of 1840 sagged downward about 100 meters, and in the southwestern portion of this sunken area, at Halemaumau, an inner conical pit 1,000 meters in diameter at the top and 150 meters deep was formed. The volume of collapse was somewhat less than that of 1840. During the following months the central depression was again gradually filled. By 1874 the cone around Halemaumau had reached a height nearly equal to that of the southern wall of the caldera, and lava streams from it were pouring northward into the central depression. The lava disappeared briefly from Halemaumau in April 1879, but there was no general subsidence in the caldera, and the lake of molten lava reappeared within about a month.

In 1886 a subsidence of the area immediately surrounding Halemaumau produced a roughly triangular pit about 900 meters across and 100 meters deep, with a small pit 85 meters deep in its floor. This depression was soon refilled:

but 5 years later, in 1891, another similar collapse occurred. This also was restricted to the immediate area of Halemaumau. Refilling of the pit started almost immediately, and by July 1892 the lake was again overflowing.

From 1823 to 1894 activity at Kilauea was essentially continuous. There were many intervals, especially just after the great subsidences, when liquid lava disappeared from the crater, but all were brief. Active lava returned within a few days or weeks of its disappearance.

During July, 1894, a spectacular minor subsidence occurred at Halemaumau, lowering the level of the lava 80 meters below the rim of the pit. The first rapid subsidence was followed by slower sinking of the lava level, but activity continued in Halemaumau at depths of 100 to 200 meters until December 1894, when the molten lava disappeared altogether. The diameter of the pit at that time was approximately 300 meters. From then until 1907 only occasional brief spells of activity occurred deep in the pit, although there appears always to have been fume visible. This 13-year interval of relative quiescence was the first real break in the continuity of the activity at Kilauea since before 1823.

From 1907 until 1924 the volcano was again almost continuously active. Spectacular but minor collapses occurred at Halemaumau in 1916, 1919, and 1922. The collapse of 1919 was associated with drainage of lava from the lake into fissures of the southwest rift zone, and an eruption on that rift zone 9 kilometers from the caldera. The collapse in 1922 accompanied a small eruption on the east rift zone, 11 kilometers from the caldera. Still another small eruption occurred in August 1923 about 9.5 kilometers southeast of the caldera. In May 1924 occurred the greatest collapse since 1840, accompanied by strong phreatic explosions caused by ground water entering the hot throat of the volcano (Jaggar and Finch, 1924). The collapse and accompanying explosions enlarged Halemaumau from a nearly circular pit 425 meters in diameter, to one with rim diameters of 915 and 1,035 meters and a depth of 400 meters.

The great collapse of 1924 was accompanied by very numerous earthquakes, cracking of the ground, and faulting along the east rift zone in the eastern part of the Puna district, near the east cape of the island of Hawaii. No eruption of molten lava occurred above sea level, but it has been suggested (JAGGAR, 1934) that eruption occurred unobserved below sea level, east of the island.

Lava activity returned to Halemaumau in July, 1924, and 7 brief eruptions between then and 1934 (MACDONALD, 1955, p. 27) raised the level of the crater floor approximately 160 meters.

Then began a period of complete quiescence of nearly 18 years, ended only by the outbreak in June 1952. During that period there were occasional signs of subsurface activity. In November 1944 earthquakes and tumescence of the volcano indicated a rise of magma beneath the caldera region. No eruption occurred, however, and in early December a reversal of tilting of the ground surface indicated that the magma column was subsiding again (FINCH, 1944). In December 1950 marked ground tilting accompanied by a large number of earthquakes indicated a subsidence of the top of the Kilauea shield, presumably reflecting a reduction of magmatic pressure beneath it (FINCH, 1950; MACDONALD, 1954, p. 175). Through all of the 18-year period of quiescence not even mild fuming was observed at Halemaumau.

The gradual reduction in size of the sunken depression within the caldera strongly suggests a corresponding decrease in the diameter of the mobile mass (presumably the magma column) underlying the caldera. From 1886 onward it appears to have had only about the dimensions of the present Halemaumau. This, together with the lessening frequency of eruption, suggests that there may have been an overall decrease in the general activity of the volcano during the last 1.5 centuries.

Earthquakes during 1951 and early 1952

The new period of activity of Kilauea volcano appears to have begun with a strong earthquake centered near the caldera on the afternoon of April 22, 1951. The quake, which occurred at 14:52:21 Hawaiian standard time (10 hours behind Greenwich civil time), was the strongest experienced in the region since 1929, and possibly since 1908. It was felt generally all over the island of Hawaii, and by many persons on the islands of Maui and Oahu, more than 300 km away, but only minor damage resulted. It was assigned a magnitude of 6.5 on the Richter scale by the Seismological Laboratory of the California Institute of Technology. The intensity of 5 (modified Mercalli) was essentially uniform for a distance of 50 km northeast and southwest of Kilauea caldera.

All seismographs on the island of Hawaii were dismantled by the preliminary waves, and time control on most of the instruments was poor. Consequently neither the epicenter nor the depth of origin could be determined instrumentally. The direction of first motion of the ground at seismograph stations on the rim of Kilauea caldera was south, east, and down, indicating an origin probably southeast of the caldera. There appears to be no question that the quake originated beneath the general summit region of Kilauea volcano, and probably on the east rift zone within a few kilometers of the caldera. Large amplitude on the vertical seismograph as compared to that on the horizontal pendulums, coupled with the uniformity in intensity over a wide area, suggests that the quake originated at moderately great depth, probably at least 30 km.

The major earthquake was preceded by a quake of moderate size, at 4:53:53 (H.s.t.) on the same day. This quake originated on the east rift zone of Kilauea 16 kilometers east of the caldera, at a depth of about 30 kms. During the week following the major quake 108 smaller earthquakes were recorded at Kilauea caldera. Almost all of those large enough to be located fell into two groups, one of which originated beneath the caldera and nearby parts of the east and southwest

rift zones, and the other along the faults of the Kaoiki system between Kilauea and Mauna Loa.

Tilting of the ground surface accompanying the major earthquake suggested a sharp subsidence of the summit of Kilauea, but on April 24 there commenced a rapid northward tilting of the ground surface at the northeast rim of the caldera, apparently indicating tumescence of the volcano. The rapid northward tilting continued until early August.

On August 21 a violent earthquake (intensity 7 m.M., magnitude 7 Richter) occurred close to the western shore of the island of Hawaii. This quake was the most severe in Hawaii since 1868, but it had no apparent direct relationship to the volcanic activity, and it will not be further discussed here. It has been described in detail elsewhere (Macdonald and Wentworth, 1952; 1954, pp. 185-213).

On September 16, at 1:43 (H.s.t.), another earthquake with an intensity of 5 (m.M.) originated on or near the Kaoiki fault zone. It was followed by 21 smaller aftershocks from the same region. Still another swarm of small quakes originated along the Kaoiki fault zone between October 1 and 6.

During the late months of 1951 both volcanoes were uneasy. On November 8, at 9:34, a quake of intensity 6 (m.M.) originated at shallow depth beneath a point at about 1,370 m. altitude on the southwest rift zone of Mauna Loa. During both November and December many smaller earthquakes came from foci on the rift zones of Kilauea and Mauna Loa, and on the Kaoiki fault zone. On December 6, at 20:19, a strong earthquake occurred on the east rift zone of Kilauea about 22 kilometers east of the caldera. Between December 3 and 7 the ground at the northeast rim of Kilauea caldera tilted southward 4.4 seconds, and a slow southward tilting of an additional 0.6 second continued until December 16, indicating a sinking of the caldera region possibly as a result of drainage of underlying magma into the opening east rift zone. Between December 16 and 25, however, the ground tilted northward again 2.6 seconds. Thus there appears to have been a rapid fluctuation of pressure beneath the summit of Kilauea.

Fluctuation of this sort may be as important as tumescence in indicating the mobility of the magma column near the surface, and potential eruptivity of the volcano.

In the spring of 1952 seismic activity on the island of Hawaii reached the highest peak it had attained for many years. Some of the earthquakes originated in Mauna Loa, but by far the greater proportion had their origins in Kilauea, or beneath the ocean just south of Kilauea.

During January and February the number of earthquakes was approximately normal for a period of volcanic quiet. Most of the foci that could be located lay in the vicinity of the caldera or along the east rift zone of Kilauea. On March 13 a strong earthquake centering south of the island marked the beginning of an enormous swarm of submarine quakes that continued through the rest of March and April. On March 16 the Volcano Observatory seismographs recorded 39 earthquakes, but on succeeding days the number rapidly increased to 359 on March 20, nearly all of them from foci south of the island. Following that maximum the number of quakes slowly decreased, at a fairly regular rate, over the next 6 weeks. By the end of April the total number of quakes recorded from the area just south of the island exceeded 4,000. Of these, approximately 185 could be located with reasonable precision.

The submarine earthquakes have been described in more detail elsewhere (MACDONALD, 1952, 1955a). Their epicenters fell in a narrow nearly east-west zone 10 to 25 kilometers off shore (fig. 1). The zone extended across the southern side of a broad domical bulge of the south slope of the island that probably represents a submerged shield volcano similar in outline to Kilauea above sea level. Careful watch revealed no signs of submarine eruption. Possibly eruption in water of such great depth (averaging about 2,000 meters) might not produce any effects recognizable at the surface of the ocean. In addition, however, no volcanic tremor such as typically accompanies Hawaiian eruptions was recorded on the seismographs. The most probable interpretation of the earthquakes

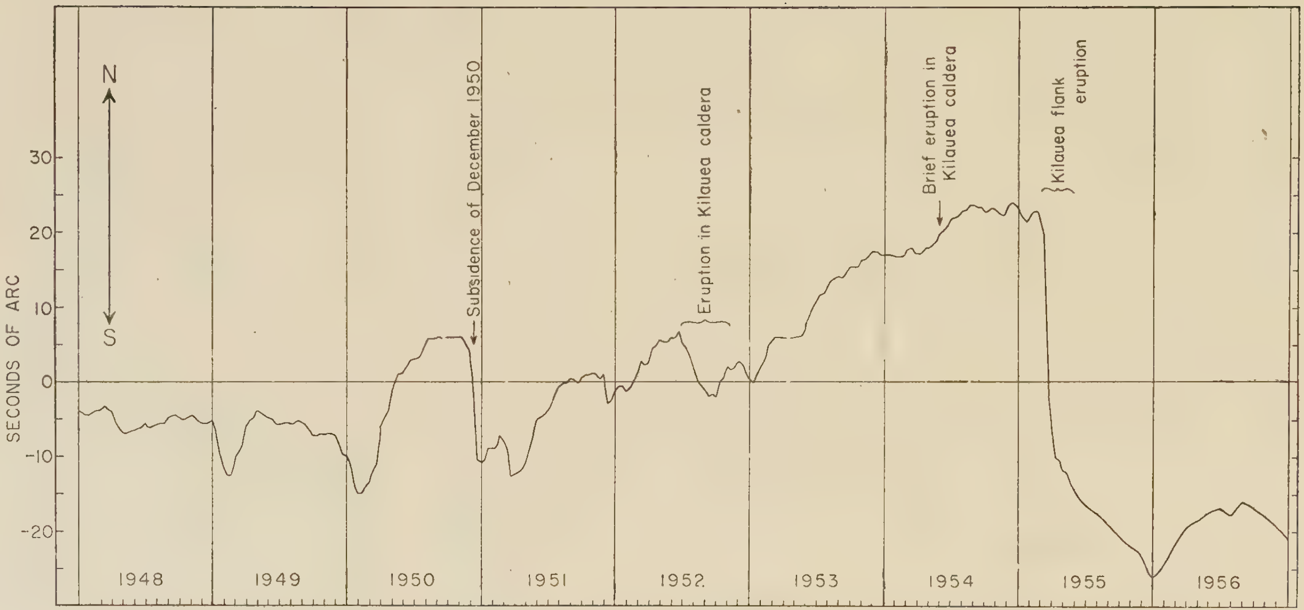

Fig. 2 - Curve showing departure of the north-south tilting of the ground at the northeast edge of Kilauea caldera from the normal annual curve, from 1948 to 1956.

is that they were caused by movement along a zone of marginal faults crossing the south slope of the submerged shield in the same manner the faults of the Hilina system cross the southern slope of Kilauea (fig. 1). Movement on the faults probably resulted from an uplift of the crest region of Kilauea, as part of a general tumescence of the volcano. It is noteworthy that during the same period a few quakes originated on the Hilina system, indicating movement along those faults also.

Early in April, particularly on April 5-7, a swarm of several dozen earthquakes originated on the east rift zone of Kilauea, from the caldera to a point about 13 kilometers southwest of the town of Pahoa (fig. 1). Numerous earthquakes from the same region continued through the rest of April and May. During June many quakes, mostly small and of shallow origin, originated beneath the caldera region. Between the 19th and 27th of June the seismographs recorded 84 such quakes. During the same period there were also several quakes from the Kaoiki fault zone, between Mauna Loa and Kilauea, probably resulting from vertical adjustments caused by the tumescence of Kilauea. Thus during the months of April, May, and June, Kilauea was distinctly restless.

From the beginning of March to mid-May there was essentially no tilting of the ground in the north-south azimuth at the north-eastern rim of Kilauea caldera. Because at that season of the year the ground at that station normally is tilting southward, this absence of tilt represents a negation of seasonal tilt by volcanic tilt, and consequently a tumescence of the volcano. Between March 1 and late May the curve of measured north-south tilting departs from the normal curve by approximately 5 seconds of arc (fig. 2). This represents a rise of the ground surface east-northeast of Halemaumau of only about 4.5 cm. in relation to the station on the caldera rim, but because the tilting unquestionably extended an unknown distance beyond the station, the total rise may have been considerably more than that.

No definite pattern of earthquake foci starting at con-

siderable depth and gradually approaching the surface, such as was found preceding some earlier eruptions (Finch, 1943), was recognized in 1951 and the spring of 1952, although in a general way the big earthquake of April 1951 almost surely came from considerably greater depth than most or all of the later quakes. In retrospect it appears, nevertheless, that the earthquake activity combined with the tumescence of the volcano should have been sufficient evidence for at least a tentative prediction of coming eruption. In early May, and again in early June, press releases did call attention to the uneasiness of the volcano, but at the time it was not felt that the evidence was sufficient to justify a prediction of imminent eruption. My attention was perhaps too strongly held by the great swarm of submarine earthquakes – a phenomenon without precedent during the time of operation of the Hawaiian Volcano Observatory. Without this complicating factor the significance of the definite, though small, tumescence and the less conspicuous earthquakes along the east rift zone and beneath the caldera might have been clearer.

The 1952 eruption of Kilauea

On June 27, at approximately 23:40 Hawaiian standard time, Kilauea erupted. The eruption has been described in detail elsewhere (Macdonald, 1952a, 1955a), and only a brief summary is given here.

Spouting lava reached the surface along a newly-opened fissure that extended about 700 meters in a southwest-northeast direction across the floor of Halemaumau crater and part way up the walls, (fig. 3). Along most of the length of the fissure the lava fountains ranged in height from 15 to 50 m, but at the southwestern end a fountain more than 240 m high played to a level above the rim of the crater. A flood of lava poured from the fissure over the crater floor, and in half an hour had formed a pool more than 10 m deep. A dense fume cloud rose from the crater and was blown southwestward by the trade wind. Falling pumice, some of the blocks

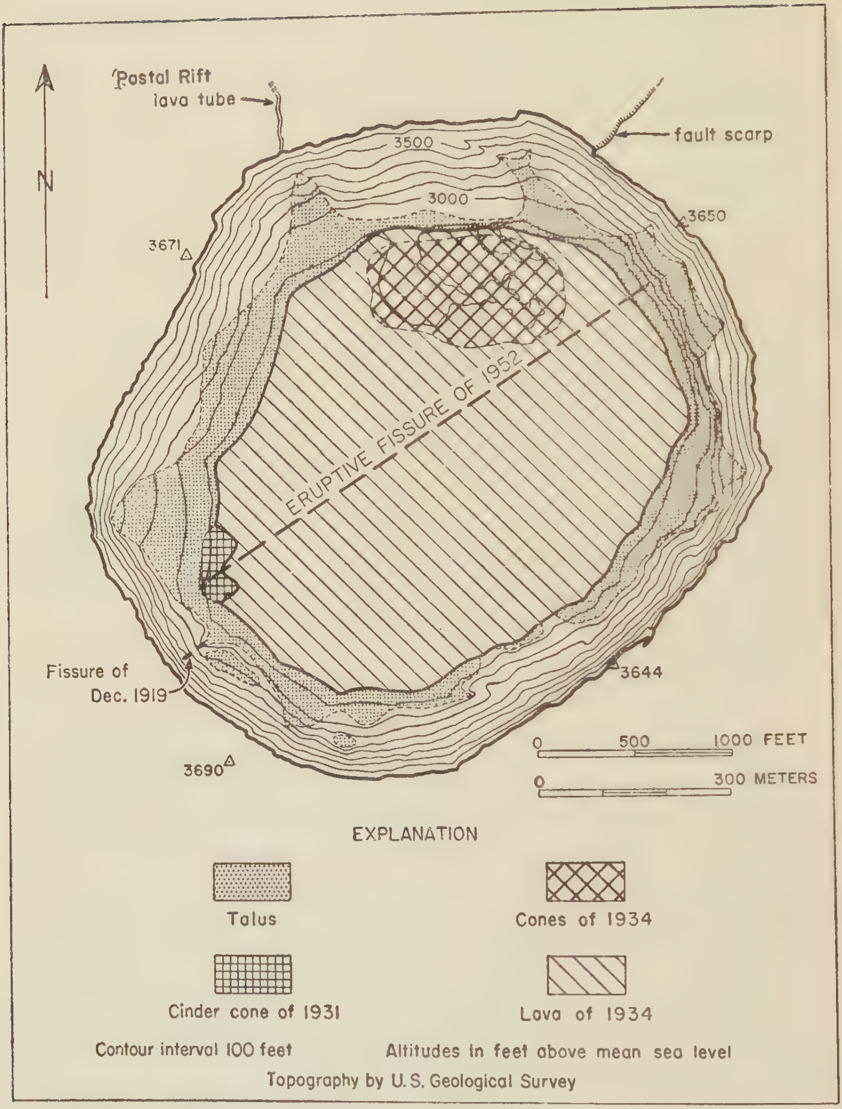

Fig. 3 - Map showing the condition of Halemaumau crater just before the 1952 eruption, and the position of the eruptive fissure of 1952. The fissure of December 1919 is that through which lava drained from the Halemaumau lake to feed the lava flow of 1919-1920 on the flank of the volcano 10 kilometers to the southwest.

as much as 25 cm in diameter, formed a heavy blanket over the caldera floor south-west of Halemaumau.

About 3,000,000 cubic meters of lava was poured into the crater during the first half hour of the eruption. The rate of extrusion soon started to diminish, however, and the size and extent of the fountains decreased. Within 15 minutes of the first outbreak the big southwestern fountain was less than 200 m high, and in 30 minutes it had decreased to about 120 m (plate 1). By 04:00 on June 28 the southwestern part of the fissure was completely inactive, and only weak activity continued along the northeastern portion. Briefly, it seemed that the eruption might be coming to an end.

During the early hours of the eruption the lava covering the crater floor appeared extremely fluid. Agitation of the liquid by the fountains set up series of waves that swept across the surface and washed up and down 3 to 5 m on the crater walls. The dark crust that quickly formed on the lake was only a few centimeters thick, and somewhat flexible, but was continually being torn apart to reveal the incandescent golden yellow liquid beneath it. Convective circulation quickly developed in the growing pool, and a true lava lake was established. Lava rising along the feeding fissure moved outward in all directions, but in distinct currents, and sank again around the edges of the lake. Where the lava sank, secondary fountains a meter or two high were formed, apparently as a result of the release of gas that had been entrapped in the fragments of crust that were dragged down with the fluid lava and at least partly remelted. Most of these secondary fountains lasted only a few seconds, then disappeared, to be replaced by others at other places; but at places where the principal currents plunged downward more or less continuous secondary fountains were formed.

About 04:20 fountains reappeared along the southwestern part of the fissure, and activity again gradually increased. By daylight the old floor of Halemaumau was submerged beneath a pool of liquid lava more than 16 m deep. About 6,000,000

cubic meters of new lava had been poured into the crater in 6 hours.

On the morning of June 28 the discharge of lava was accompanied by very little gas release. The small fountains along the southwestern part of the fissure consisted mostly of a quiet outwelling of very fluid lava, with very little fume. Some gas was given off along the northeastern part of the fissure, where at 05:00 there were three small blowing vents, and by 06:30 a double fountain had built a small spatter cone on the slower slope of the northeast talus und was spurting to heights of about 10 m, with occasional bursts reaching 20 m. On the whole, however, the amount of gas being released was very small. It was as though the initial extremely voluminous burst had used up the head of gas accumulated in the upper part of the magma column before eruption, and the later lava was derived from a lower gas-impoverished portion. At about 06:00 one of the small fountains near the southwestern end of the fissure began to grow, and by 06:15 it was a brightly incandescent dome about 8 m across, resembling the dome of water above a freely-flowing artesian well. By 07:15 the dome fountain occasionally was reaching heights as great as 16 m (plate 2). The up-welling lava still gave off very little gas.

By late morning on June 28 the proportion of gas being liberated was again becoming more normal. The northeastern vents had nearly ceased activity, but the fountains along the southwestern part of the fissure were growing in size. The principal fountain, close to the foot of the southwestern wall of the crater, was 20 to 30 m high, and had again become a typical semi-explosive flinging fountain resembling a pulsating high-pressure jet of water from a hose. Early in the afternoon a prominent sinkhole developed over the feeding fissure about 200 m southwest of the northeast wall of the crater, and lava streamed toward it from all directions. A slump scarp 3 to 5 m high had formed around the edge of the lake, leaving a narrow bench of congealed lava clinging to the crater wall. The lowering of level of the central part of

the lake may have resulted partly from drainage of lava back into the feeding conduits, but probably it was largely the result of shrinkage of the lava in the lake because of cooling and loss of gas.

In the afternoon the fountains near the foot of the south-

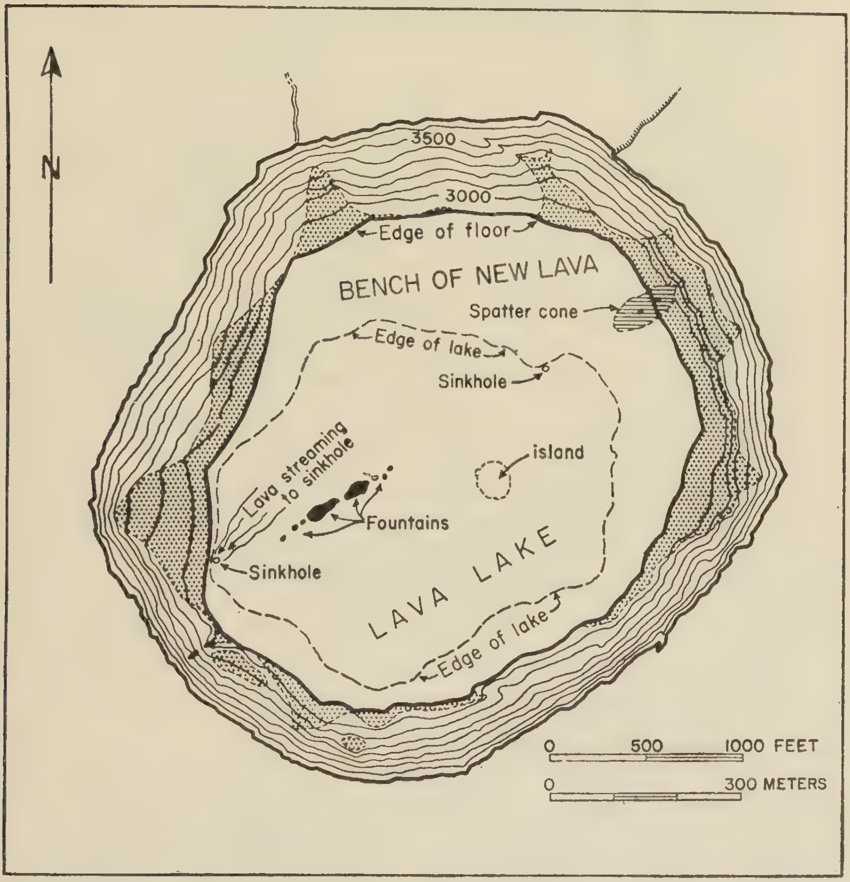

Fig. 4 - Map showing conditions in Halemaumau crater on July 1, 1952.

west wall of the crater became small and sporadic, but a new fountain just northeast of them gradually grew to a height of about 45 m. Late in the evening a second very active sinkhole developed at the site of the fountains near the base

of the southwest wall. Pale blue flames 2 to 5 m long played over the mouths of the conelets at the northeast edge of the crater.

On the morning of June 28 the lake had an area of 404,000 m^2. Over the next few days a bench of semisolid lava gradually grew around the edge of the pool, and the area of the lake decreased. By July 1 (fig. 4) il was reduced to 283,000 m^2, and by mid-July to 138,000 m^2. From time to time fragments as much as 50 m across became detached from the bench and formed islands in the lake. These islands moved slowly across the lake toward the fountains, presumably carried along by a return circulation in the lower part of the lake. The islands appeared to be actually floating, inasmuch as they rose and fell with the level of the liquid around them ! One large island, which became detached from the bench early on June 29, reached the central fountain area on the evening of June 30. Its speed of movement thus was about 250 m in 36 hours. About 18:30 it moved directly over the northeasternmost small fountain and immediately started to disappear, partly by crumbling away of its edges, and partly by foundering. On July 1 it had broken into two small islands, which moved to positions just east and northwest of the principal fountain. By nightfall these islands appeared to be grounded. Instead of rising and falling with the surrounding liquid, as they had done previously, they remained essentially stationary while the liquid lava around them rose and fell with the surges from the fountains.

The fountains at the northeastern end of the fissure continued weakly active until July 5, building spatter cones about 15 m high. The sinkhole near the southwestern end continued active, with occasional reversals to primary fountain activity, until mid-July. On July 3 and 4 short-lived fountains at that site threw some bursts as high as 200 m. By the afternoon of June 30 the widening bench was encroaching on the northeast sinkhole, and on the afternoon of July 1 the sinkhole was replaced by a constant fountain 20 to 30 m high. Spatter from this fountain accumulated on the adjacent bench and

built a beehive-shaped conelet. By July 4 the conelet had

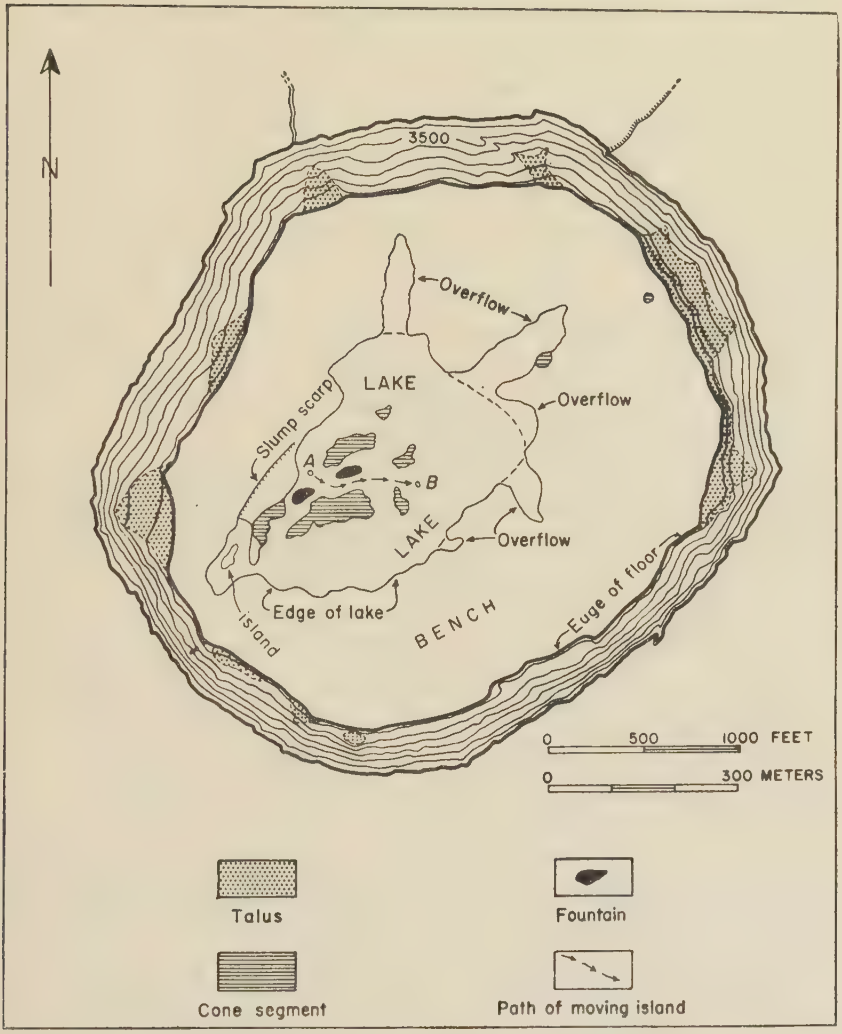

Fig. 5 - Map showing conditions in Halemaumau crater on July 25, 1952. A small island, consisting of a detached segment of the spatter cone, moved from point *A* at 14:30 to point *B* at 17:10.

become nearly sealed over by its own spatter, and after that time it exhibited no more activity.

A chain of about 20 small fountains across the south-

western part of the crater floor continued active throughout the first two weeks of the eruption (pl. 3). During the first three days the deep pool of fluid lava prevented the accumulation of spatter around the central fountains, but by the night of June 30 there appears to have been a sufficient accumulation of pasty material on the bottom of the lake to support islands adjacent to the fountains. Thereafter much of the ejecta accumulated to form cones around the central fountains. About July 11 the active length of the fissure became restricted to approximately 120 m, and the two principal fountains 100 m from the southwest wall of the crater began building a large cinder and spatter cone. Rivers of lava continued to pour out through gaps in the cone walls and feed an active lava lake around the cone.

About July 5 spatter from secondary fountains around the edge of the lake started to build a wall, or levee (« lava ring » of R. A. Daly) on the inner margin of the bench (pl. 4). Through the succeeding month the lava ring held the lake at increasingly higher level above the surface of the bench. At times the level of the lake stood as much as 7 m above the adjacent bench. Occasional overflows, or break-downs of short segments of the ring, released streams of lava over the surface of the bench (fig. 5), and other small flows on the bench surface originated from fissures within the bench itself.

Activity continued essentially the same for nearly a month. The two principal fountains, in the southwest central part of the lake, were 15 to 25 m high, throwing occasional bursts as high as 50 m. The cone around them was 15 to 20 m high, and from it two rivers of very fluid lava escaped to feed an encircling lake (pl. 4 and 5) in which the lava moved outward across the surface and downward at the edges. Some fluctuations in the strength of activity occurred, and other small primary fountains were active at times, particularly in a southern lobe of the lake.

Early in August the explosiveness of the fountains increased somewhat, suggesting an increase in the viscosity of the lava, which was indicated also by its general appearance

during flow. This was accompanied by a gradual decrease in

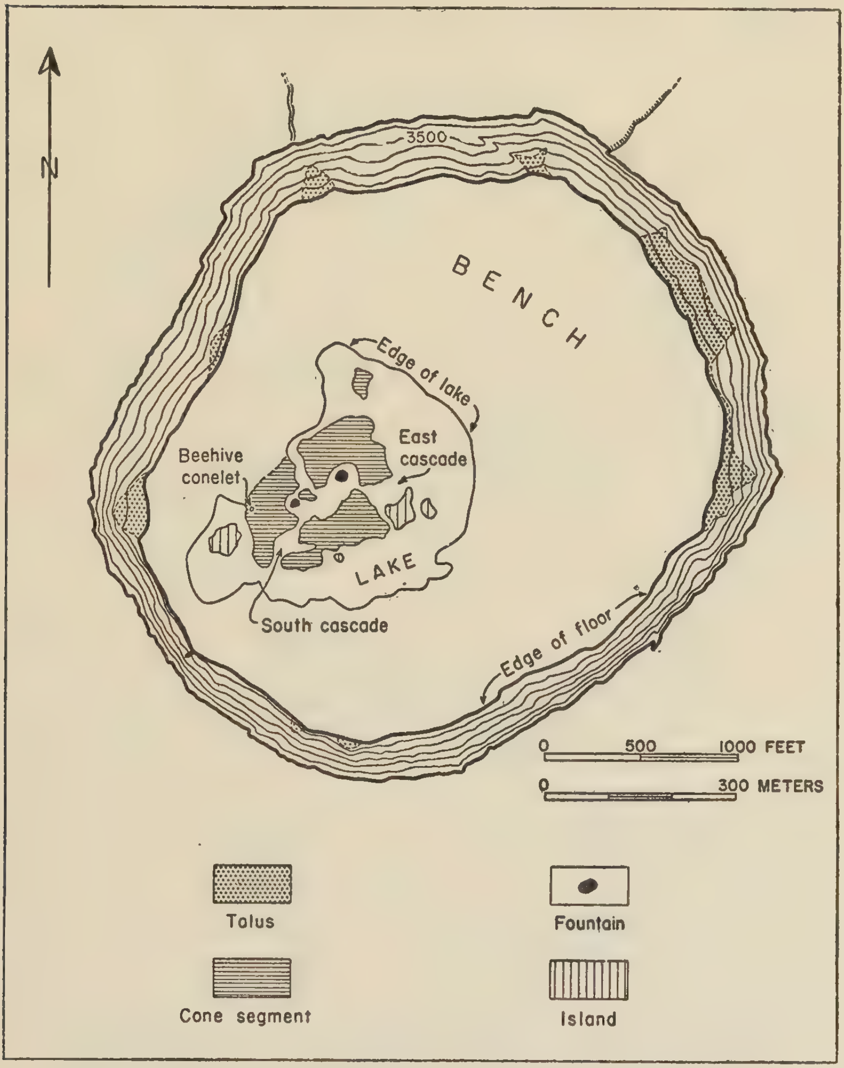

Fig. 6 - Map showing conditions in Halemaumau crater on August 12, 1952. The beehive-shaped spatter conelet was built by an intermittent semi-explosive lava fountain.

temperature and volume of material being extruded. On August 6 and 7 explosive bursts from the northern fountain

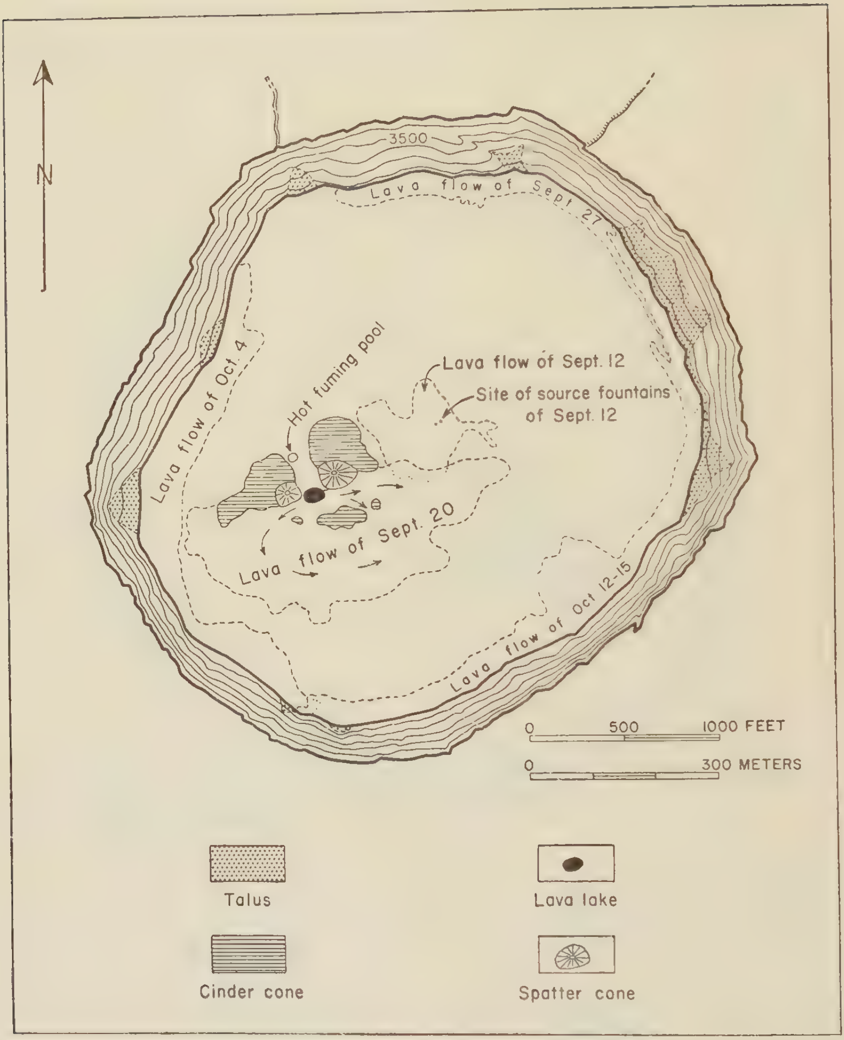

Fig. 7 - Map showing conditions in Halemaumau crater on October 21, 1952, and lava flows formed between September 12 and October 15. Buried portions of the flow margins are shown by dotted lines.

reached a height of 170 m. The area of the lava lake decreased rapidly (fig. 6).

By late August overflow from the central cinder cone had

largely ceased. Two active vents were building conelets of spatter in the crater of the larger cone. Between the conelets was a small circular lava lake approximately 30 m across

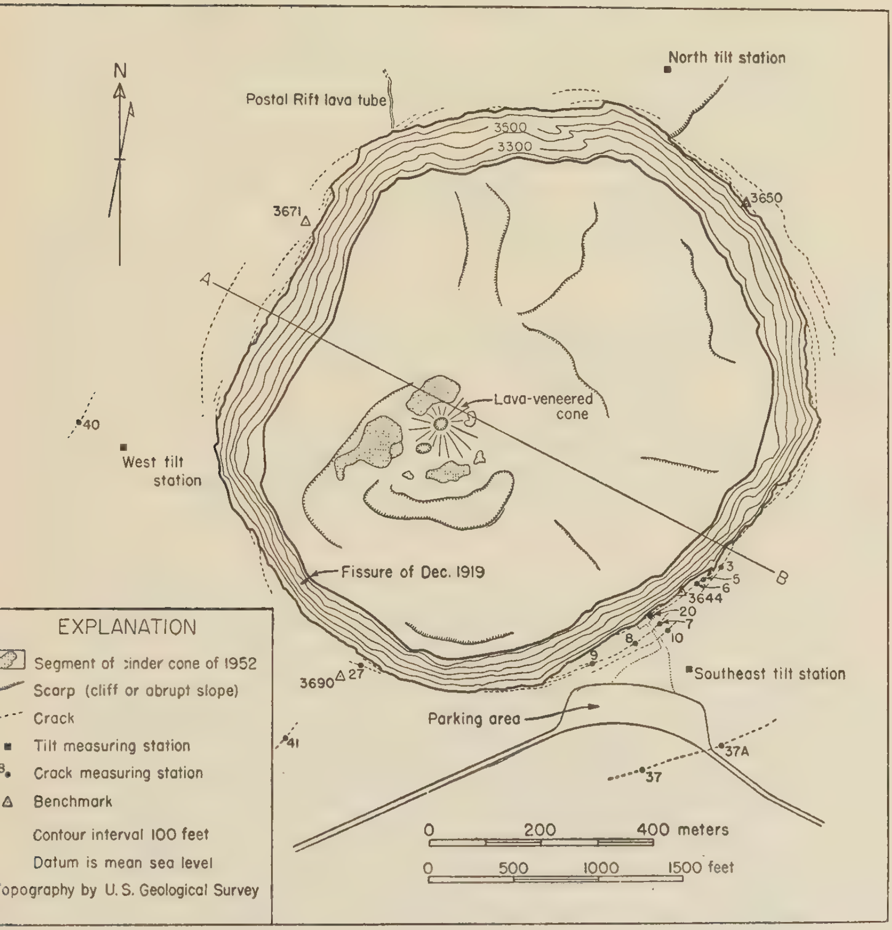

Fig. 8 - Map showing conditions in Halemaumau crater during 1953, and line of cross section in figure 9.

(pl. 6). These conditions persisted until the end of the eruption (fig. 7). Activity died down greatly in late August, and for a time it appeared that the eruption was about to end. However, at the beginning of September activity revived, and contin-

ued until early November. Through most of this period the northern vent was the more active, and circulation in the small lava lake was from north to south. From September 19 to 22 conditions became reversed, with the southern vent the more active and circulation in the lake from south to north. On September 22 conditions again reversed, and for the rest of the eruption the northern vent remained the more active

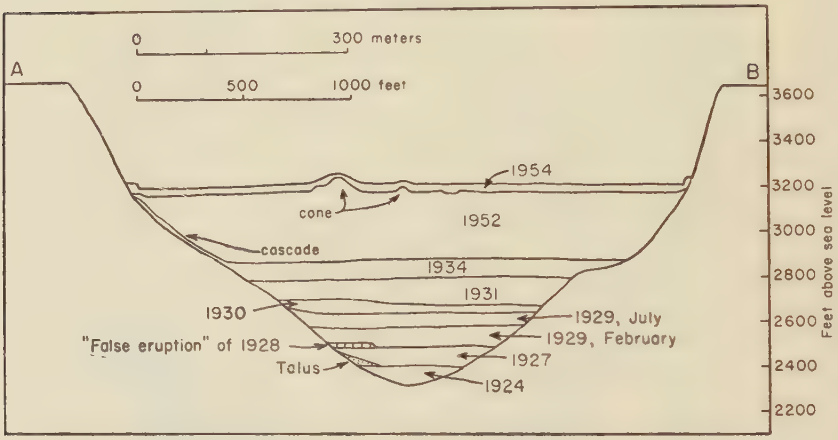

Fig. 9 - Cross section of Halemaumau crater along line A-B, figure 8, showing filling of the crater from 1924 to 1954.

and lava in the lake rose near the northern edge, moved southward across its surface, and sank at the southern edge.

Flows appeared from time to time on the floor of the crater outside the central cone and lake (fig. 7). Some of these rose along the trace of the original eruptive fissure, but many rose at the junction of the crater floor and wall. The latter appear to have been squeezed up along the surface of discontinuity between the old crater wall and the mass of new lava. The surface of the entire crater floor rose slowly and more or less continuously. Part of the rise was caused by addition of new lava by flows over the surface, but much of it was caused by bodily elevation of the floor, apparently resulting from intrusion of new lava into the still hot and mobile lower portion of the new crater fill.

The eruption ended on November 10. The depth of the new lava in Halemaumau averaged 125 m, and its volume was approximately 49,000,000 cubic meters. At the end of the eruption the depth of Halemaumau crater, from rim to floor, averaged 140 m (figs. 8 and 9).

The only specimens of the new lava obtained were fragments of pumice thrown out of the crater. The pumice consists of basaltic glass with a refractive index of 1.598 ($\pm$ .003), and a silica content of 50.01 percent. An analysis of the pumice is given elsewhere (MACDONALD, 1955, table 11, column 6; 1955a, table 10). The radioactivity was less than 5 parts per million of uranium equivalent. The very low radioactivity of the solid materials produced during recent Hawaiian eruptions make it very improbable that any important part of the magmatic heat is directly derived by breakdown of radioactive materials.

Calculations based on very rough data indicate that the average gas content of the magma reaching the surface through the entire eruption was of the order of 0.4 weight percent.

The calculated viscosity of lava spilling out of the central cone on August 12 and 13 ranged from 1.9×10^4 to 3.8×10^4 poises. No favorable conditions for calculating viscosity were encountered earlier in the eruption, but the general appearance and behavior of the lava indicated that it probably was appreciably less viscous during earlier stages.

Temperature measurements were made with optical pyrometers by me throughout the eruption, and by Prof. J. J. NAUGHTON of the University of Hawaii, on July 2 and 3. Applying corrections for the emissivity of the lava, and for the absorption of radiation by intervening fume and haze and the screening effect of falling ejecta around the edges of the lava fountains (MACDONALD, 1955a, p. 85), it was found that the temperature of the cores of the main fountains throughout July was about 1145°C. On the first two days of the eruption it probably was as high as 1155°. Early in August there commenced a rapid drop that brought it to about 1055° in late

August. Through July the temperature at the surface of the lava lake was generally about 1005°.

The heat energy released during the eruption was enormous. If we assume the specific heat of the lava to be 0.25 cal/gr/°C, the heat of fusion to be 50 cal/gr, the temperature of the erupting lava to be 1100°C, and the average density of the lava to be 2.7 (about the average density observed in similar consolidated crater-filling pools), the heat released would be approximately 878 million calories per cubic meter of erupted lava. On this basis the heat liberated during the entire eruption would be approximately 4.3×10^{16} calories, or in work equivalent, 1.8×10^{24} ergs. Both seismic and explosive activity were very minor, and the heat loss may be regarded as approaching the total energy release of the eruption. It is roughly equivalent to YOKOYAMA's (1957, p. 96) estimates of the total energy released in other volcanic eruptions of moderate size.

Earthquakes and ground tilting during 1953 and early 1954

Mauna Loa showed no apparent reaction to the 1952 eruption of Kilauea. From early May to mid-June, 1953, there may have been a slight tumescence of Mauna Loa, but during late July and early August there was slight detumescence, probably indicating a relaxation of magmatic pressure beneath the volcano. During the week starting November 29 more than 700 small earthquakes originated at shallow foci along the northeast rift zone, but there were no other signs of activity of the volcano.

There was essentially no detumescence of Kilauea volcano following the eruption of 1952, and the magma column probably remained standing at a high level in the conduits. It was recognized that under such conditions a new outbreak might come with little or no specific warning. Furthermore, tumescence soon began again. From December 1952 to late April 1953, measurements of ground tilting at the north-northeast edge of Kilauea caldera indicated a very slow slight

swelling of the volcanic structure. Seismic activity during this period was approximately normal for times of volcanic quiet. Several sharp earthquakes from the Kaoiki fault zone may have resulted from adjustments between the swelling Kilauea structure and a stationary or slightly shrinking Mauna Loa.

On February 28, 1953, seismographs at Kilauea caldera recorded 18 minutes of continuous « harmonic » tremor, of the sort we have come to associate with the movement of magma in the conduits of the volcano. Similar tremor was recorded for 16 minutes on March 14, and 13 minutes on March 29. Apparently, magma was moving at some fairly small depth within the volcano. On April 29 three moderate earthquakes originated on the southwest rift zone of the volcano.

On May 17 the rate of northward tilting at the north-northeast edge of Kilauea caldera increased greatly. This was followed, on May 20, by an increase of local seismicity. Through late May the number of quakes recorded on the Bosch-Omori seismograph averaged 20 per day, about 10 times the normal. More than 90 percent of them came from shallow foci in the caldera region. The uneasiness continued through June, when northward tilting was approximately 5 times the normal for that season of the year, and seismicity was 4 times the normal. The tumescence, indicated by the northward tilting, was accompanied by opening of cracks on the caldera floor. Northward tilting continued at a rate somewhat greater than normal until mid-October. Seismicity also continued greater than normal, most of the quakes originating in the caldera region, but others coming from adjacent portions of the east and southwest rift zones. On October 27 local seismic activity reached so high a level that a continuous watch was established at Halemaumau crater. The seismic crisis passed in a few hours, however, without eruptive activity. Both northward tilting and seismicity continued slightly greater than normal through November, but were approximately normal during December.

Through the first 3 months of 1954 both ground tilting and seismicity in the Kilauea caldera region continued ap-

proximately normal for times of volcanic quiet. Early on March 30, however, the seismic quiescence was ended by two strong earthquakes that shook the entire island of Hawaii, and caused extensive moderate damage over the southeastern part of the island. The epicenters were 30 kilometers east of Kilauea caldera, and the foci about 20 kilometers below the surface, probably on the eastward extension of the Hilina fault system, but possibly on the east rift zone of the volcano (J. P. EATON, in MACDONALD and EATON, 1957, p. 55). These quakes are regarded as the beginning of the seismic prelude to an eruption on the east rift zone in early 1955. Aftershocks from the same region continued into April. At the same time, seismic activity in the caldera region showed a marked increase; and for about a week the ground surface at the north-northeast edge of the caldera tilted rapidly northward, indicating a sudden sharp tumescence of the volcano. Seismicity in the caldera region remained 2 to 4 times greater than normal through April and May, and the volcano continued to swell, though at a much lesser rate than during the week following March 30.

Thus, during most of 1953, Kilauea was distinctly uneasy, and ground tilting indicated a tumescence of the volcano, presumably resulting from an increase of magmatic pressure at depth. Quiescence during December, 1953, and early 1954, was terminated by strong earthquakes in the eastern part of the volcano on March 30, and resumption of tumescence and seismic unrest in the caldera region during April and May. Between December, 1952, and late May, 1954, there had been an accumulation of approximately 20 seconds of northward tilt (fig. 2), indicating a rise of the caldera floor east-northeast of Halemaumau of about 30 cm in relation to the station on the north-northeastern rim of the caldera. Repeatedly, attention was called to the uneasy condition of the volcano, but the evidence was not regarded as sufficient to predict eruption at any specific time.

The 1954 eruption of Kilauea

It was no great surprise, therefor, when Kilauea erupted, early in the morning of May 31. Many small earthquakes occurred during the night of May 30-31, and two of them, at 3:42 and 3:47, were large enough to awaken many persons in the vicinity of Kilauea caldera. Immediately afterward I became conscious of a peculiar very low-pitched humming or roaring sound, somewhat resembling that of a heavily laden motor truck laboring up a long grade at a considerable distance. This noise had previously been described to me by several old residents of the area, who refer to it as the noise of Pele (the goddess of the volcano), but I had never heard it before. It produced no recognizable record on the seismographs, and its origin is obscure, but it was a very definite phenomenon. At about the same time high-frequency spasmodic tremor began recording on the Sprengnether seismograph (magnification 1750) at the west edge of the caldera, and superimposed on the tremor was a series of very numerous sharp small earthquakes apparently of very close origin. A moderate earthquake occurred at 3:51, followed by one at 3:54 strong enough to dismantle the Bosch-Omori seismograph in the station on the north-northeast rim of the caldera. Both J. P. Eaton and I rushed to the station to restore the instrument to operation.

At 3:30 Dr. G. H. Ruhle, of Hawaii National Park, found conditions at Halemaumau apparently wholly normal. At 4:03, when Eaton and I entered the seismograph vault, no glow was visible over the crater. At 4:09 characteristic « harmonic » tremor started to record on the seismograph; and by the time we reached the outside of the vault, at 4:10, a dense column of fume had reached a height of 600 meters above Halemaumau and was illuminated with a bright rosy glow from incandescent lava in the crater beneath it.

At 4:20, from the Volcano Observatory 0.8 kilometer away, light fume was seen to be rising from the entire area

of Halemaumau crater, and dense columns of fume were rising at its southwest and northeast edges. The top of a lava fountain 180 to 200 m high was partly obscured by the fume at the northeast edge of the crater. Activity was entirely confined to Halemaumau.

Between 4:30 and 4:35 a fissure opened on the caldera floor northeast of Halemaumau, and lava erupted there also (pl. 7). No burst of fume was seen to precede the appearance of lava, and although the area was not under specific observation, the many persons who were already watching events from three different sides of the caldera almost certainly would have noticed such a burst of fume on the caldera floor had it occurred. Apparently the first lava to reach the surface along the fissure outside of Halemaumau was very fluid, and welled out quietly with comparatively little gas liberation and essentially no fountaining. Within a very few minutes, however, fountains were forming. At 4:35 the erupting fissure outside of Halemaumau was only about 100 meters long, but it lengthened rapidly east-northeastward and by 4:50 was about 420 meters long, with 3 other shorter chains of fountains still farther northeast (fig. 10). Very rapid flows of pahoehoe had already spread as much as 300 meters from the vents.

At 4:55 we found lava fountains active along the entire length of a fissure that extended across Halemaumau essentially, if not exactly, along the line of the principal fissure of the 1952 eruption. At the base of the southwest wall of the crater was a fountain 80 to 100 meters high (pl. 9). East-northeastward, a row of fountains a meter to 30 meters high extended directly across the remnant of the 1952 cone and on across the crater floor. Near the foot of the northeast wall was a very active fountain 200 meters high, and just northeast of it an exceedingly spectacular cascade of brightly incandescent lava plunged 100 meters down the crater wall to join the pool of lava poured out from the base of the fountains (pl. 8). Two other, shorter rows of lava fountains, 1 to 8 meters high, lay northwest of the principal row and parallel to it (pl. 9).

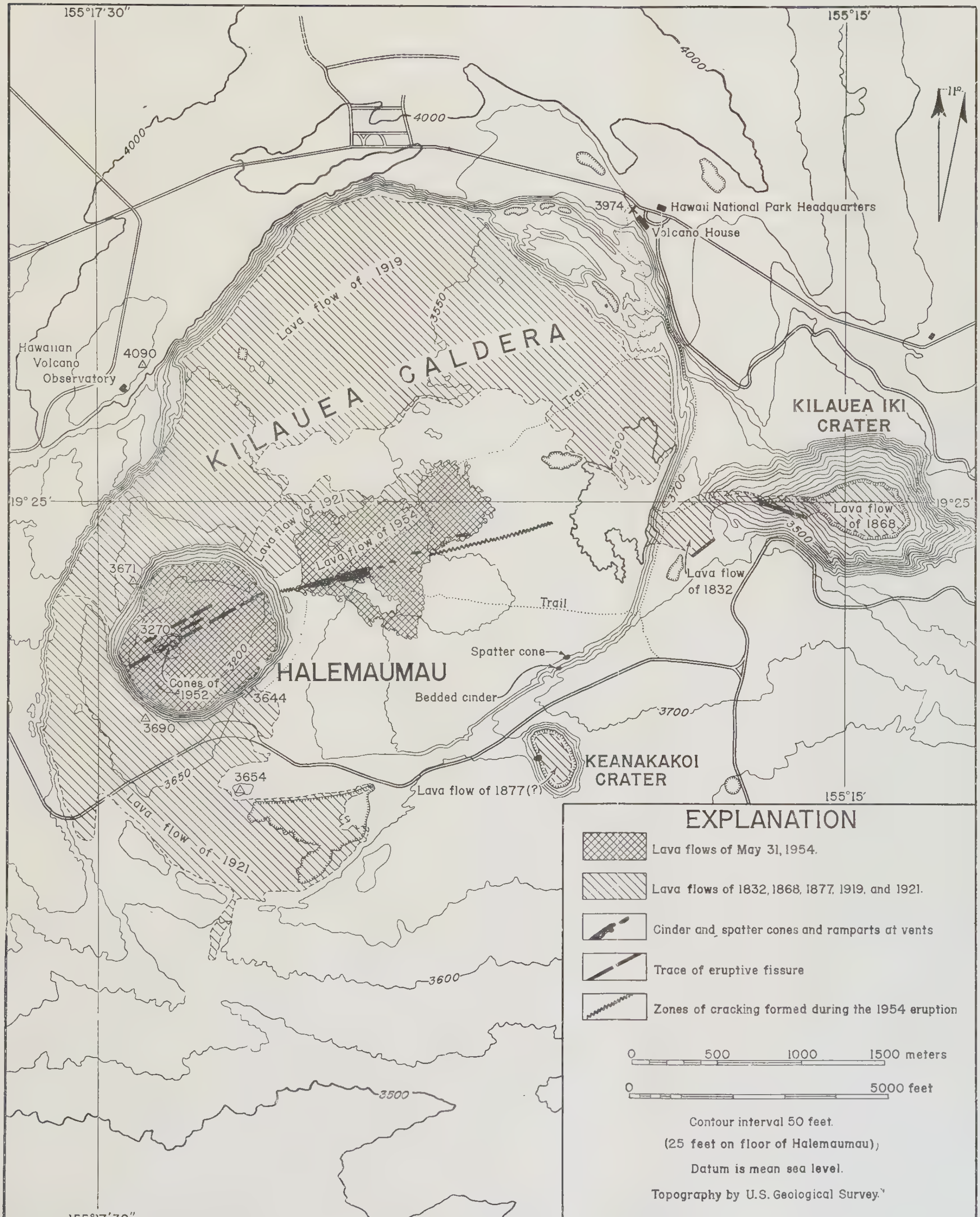

Fig. 10 - Map of Kilauea caldera showing eruptive fissures and lava flows of 1954, and some earlier historic flows.

The pond of lava had already covered the entire floor of the crater. The lava was exceedingly fluid. Surges traveled rapidly outward from the fountains and washed up and down on the crater walls, alternately covering and uncovering a bright red band 1 to 3 meters high at the base of the wall. Foundering crusts produced many secondary fountains, as they had in 1952. Most of the secondary fountains were both short lived and inconstant in position; but along certain lines, apparently marking the boundaries of convection cells in the lake, they played almost continuously. By 6:45 the depth of the pool of new lava was more than 12 meters. It is estimated that about 9.5 million cubic meters of lava had been poured into Halemaumau during the first 2.5 hours of the eruption, and 750,000 cubic meters had been poured onto the caldera floor northeast of the crater. Thus the average rate of lava emission during this interval was more than 4 million cubic meters per hour, or about 67,000 cubic meters per minute.

The strong updraft of heated air rising above the hot lava in the crater carried the fume column nearly straight upward. An attempt was made to determine the amount of radioactivity in the fume by means of a Geiger counter, but only very dilute marginal parts of the cloud could be reached. The counts obtained there showed no increase over others made on parts of the caldera floor remote from either fume or new lava. So far as the tests went, they gave no indication of any concentration of radioactive products in the voluminous early gas release of the eruption.

At 5:40 the principal line of fountains on the caldera floor northeast of Halemaumau was approximately 450 meters long. Fountains a meter to 30 meters high were almost continuous along most of the line, and showers of spatter, cinder, and pumice were building a welded spatter rampart. However, along the southwesternmost 30 meters of the eruptive fissure lava liberation had essentially ceased. Activity at the latter vents consisted mostly of a loud roaring release of gas, with occasional showers of incandescent cinder and pumice. In contrast, at the nearby cascade on the wall of Halemaumau

crater the lava was poured out quietly, accompanied by very little gas. Apparently there had been a separation of phases in that part of the eruptive fissure, most of the gas moving upward to escape at the vents on the caldera floor, while the degassed fluid lava moved laterally in the fissure to pour out in the cascade on the crater wall.

The vents on the caldera floor were separated from the rim of Halemaumau by a gap of about 65 meters, in which there not only were no active vents, but not even any well defined fissure. Instead, there were innumerable short discontinuous cracks in a zone 15 meters wide. None of the cracks was more than 3 mm. wide. Likewise, there was no sign of any well defined continuous fissure in the crater wall above the cascade.

Northeast of the principal line of vents on the caldera floor were three other lines of fountains. The flow units from all these vents merged to form a single broad flow of pahoehoe.

During the morning many small rock slides from the crater walls plunged into the lake of fluid lava in Halemaumau. The rock fragments sank quickly out of sight in the liquid, demonstrating that the specific gravity of the liquid was considerably less than that of the solid rock, and that its viscosity was rather low.

By 7:30 on May 31 activity both within and outside of Halemaumau showed a marked decrease. Within the crater the northeastern fountain was about 120 meters high, and the southwestern one about 45 m. Other fountains 3 to 15 meters high were active in the central part of the crater, but the cascade had nearly ceased.

Through the morning activity became progressively weaker. The lava flow on the caldera floor had nearly stopped spreading by 9:00. By 10:00 activity in Halemaumau was almost wholly confined to the northeast and southwest fountains, and a sinkhole was active from time to time near the center of the crater. By 11:00 activity outside of Halemaumau had essentially ceased. By 13:00 the southwest

fountain in Halemaumau was only about 15 meters high, and the northeast fountain was throwing only occasional low scattered bursts of cinder. About 13:30 there was a weak

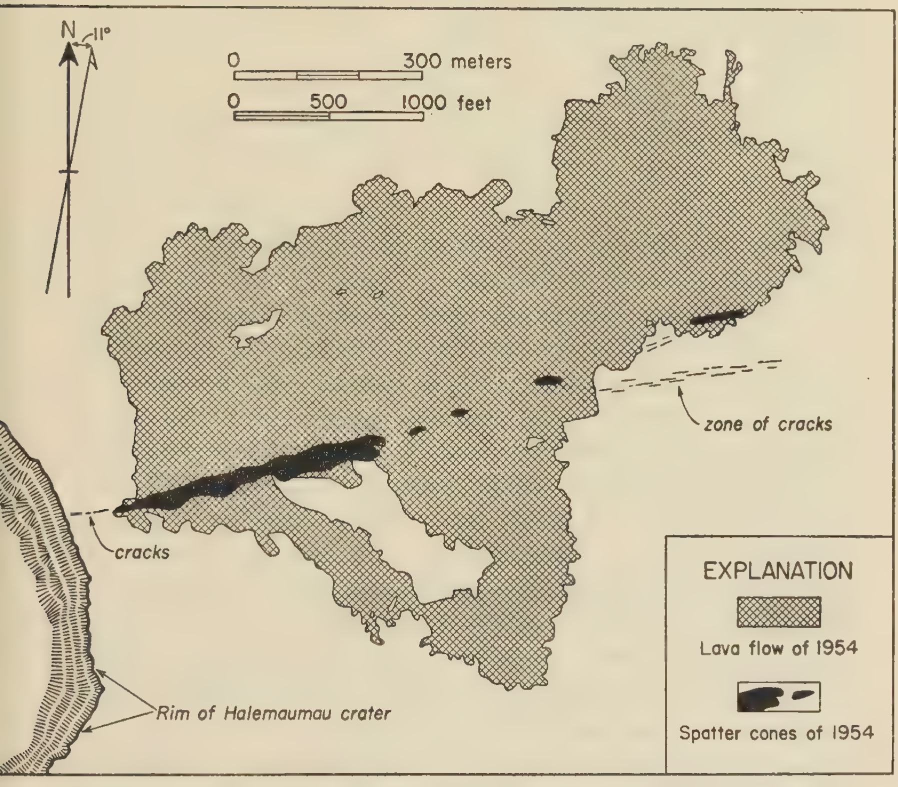

Fig. 11 - Map of the 1954 lava flow on the floor of Kilauea caldera.

reactivation of the fountains outside Halemaumau, but by 16:00 the vents were again completely quiet. The northeast vent in Halemaumau was dead, and the southwest vent was producing only weak sporadic showers of scattered ejecta to heights of about 8 meters. Similar, but even weaker activity was taking place at vents in the crater of the 1952 cone and just northeast of the cone. Activity continued essentially unchanged through the night of May 31, but the vent northeast of the 1952 cone had become the most active and

was throwing showers of incandescent cinder to a height of about 30 meters. Similar weak activity continued for the next 3 days. On June 1 and 2 there were small outflows of lava at the edge of the floor of Halemaumau. The last weak blasts from the vent near the center of the floor occurred in the afternoon of June 3.

Shortly after noon on May 31 a slump scarp had started to form around the edge of the new lava in Halemaumau. By the evening of that day the scarp was about 8 meters high, and by the end of the eruption it averaged 10 meters. At noon on May 31 the volume of the new fill in Halemaumau was approximately 11.5 million cubic meters, but by the end of the eruption it was only about 5.35 million cubic meters. Deep pools formed by rapid voluminous extrusion of fluid lava in Hawaii commonly shrink as much as 20 percent, apparently as a result of cooling and loss of gas. However, the shrinkage of more than 50 percent shown by the pool in Halemaumau during the 1954 eruption is much too great to be attributed wholly to those causes. There must have been, in addition, some drainage of lava back into the feeding conduits during the late stages of the eruption.

The lava on the caldera floor northeast of Halemaumau was almost entirely pahoehoe. In composition, it is basalt containing 1 to 2 percent of modal olivine, both as phenocrysts and as microlites in the groundmass. The rock is approximately saturated with silica, however, as it contains 4 percent of normative quartz. The chemical composition has been published elsewhere (Macdonald, 1955, p. 35, column 1; Macdonald and Eaton, 1957, p. 64). The flow on the caldera floor covered an area of approximately 560,000 square meters (fig. 11), and attained a volume of about 1,150,000 cubic meters. It was very vesicular, however, and contained many unfilled tubes and hollow toes. The volume of lava reduced to a dense state probably would not exceed 800,000 cubic meters.

Earthquakes and ground tilting during the second half of 1954 and early 1955

From the end of the eruption in Halemaumau on June 3. through the rest of 1954, Kilauea volcano remained uneasy. Seismic activity in the caldera region ranged from slightly greater than normal to three times normal. Ground tilting at the north-northeast edge of the caldera was approximately normal through most of the period, but during July and August northward tilting was slightly greater than normal, suggesting a slight further tumescence of the volcano. Neither during the 1954 eruption nor after it was there any evidence of detumescence. It appeared probable that magma remained standing at a high level in the volcanic conduits.

Most of the earthquakes recorded at the caldera came from the caldera region and the adjacent part of the east rift zone. Most of them were of shallow origin, but during December several came from a depth of about 45 kilometers beneath the caldera. Several periods of almost continuous spasmodic tremor were recorded. These seem to consist of very numerous tiny earthquakes, so closely spaced in time that the record of one overlaps the records of those preceding and following it. The longest period of spasmodic tremor lasted nearly 20 hours, from 14:00 on December 3 to 9:45 on December 4. Other periods were from 10 to 30 minutes duration. The tremor appears to have originated at a depth of 40 to 50 kilometers beneath the caldera area (MACDONALD and EATON, 1957, p. 49).

The seismic uneasiness in the caldera region continued through January and February, 1955. Ground tilting at the north-northeast rim of the caldera was approximately normal during January and early February, but on February 20 there began a marked increase of the seasonal southwestward tilting, indicating a sinking of the ground surface toward the center of the caldera.

In the light of later events, it appears probable that the sinking in the caldera region in late February resulted from

magma moving outward from beneath the summit region into the east rift zone. It is noteworthy that the beginning of the sinking corresponded roughly in time with the beginning of a marked swelling of the rift zone 30 kilometers to the east.

On April 1, 1954, a new seismograph station was put into operation at the town of Pahoa (figs. 1 and 12), 34 kilometers east-northeast of Kilauea caldera, and 4 kilometers north of the trace of the east rift zone. For the next several months the Pahoa seismograph recorded an average of about 25 earthquakes per month. In November, however, the number increased to about 60, and in December to about 90. Most of the quakes were very small, but a few were of moderate size. They appeared to originate along the east rift zone, 6 to 10 kilometers from the Pahoa station, and probably at very shallow foci.

The number of earthquakes recorded at Pahoa averaged about 6 per day in January, 1955, and increased to 15 per day between February 1 and 23. Approximately 100 earthquakes were recorded on February 24, 300 on February 25, 600 on February 26, and 700 on February 27. Many of the quakes were accompanied by dull rumblings and explosion-like noises from the ground. At the Nanawale Ranch, 5 miles east-southeast of Pahoa, throughout the afternoon of February 26 the ground was in almost constant vibration, like that caused by the passing of a heavy motor truck. In the same area the ranch dogs were much disturbed, running around excitedly, digging holes in the ground, and snuffling in the holes as though in pursuit of burrowing animals. So far as could be ascertained, however, there were no animals for the dogs to chase; nor could we detect any odor of sulfur gas in the holes they dug. The area in which the dogs were digging was almost directly in line with eruptive fissures that developed later, less than 400 meters away. Whether gas was already rising in amounts detectable to the dogs but not to us, or whether the disturbance of the animals was simply the result of the earthquakes, we do not know, but

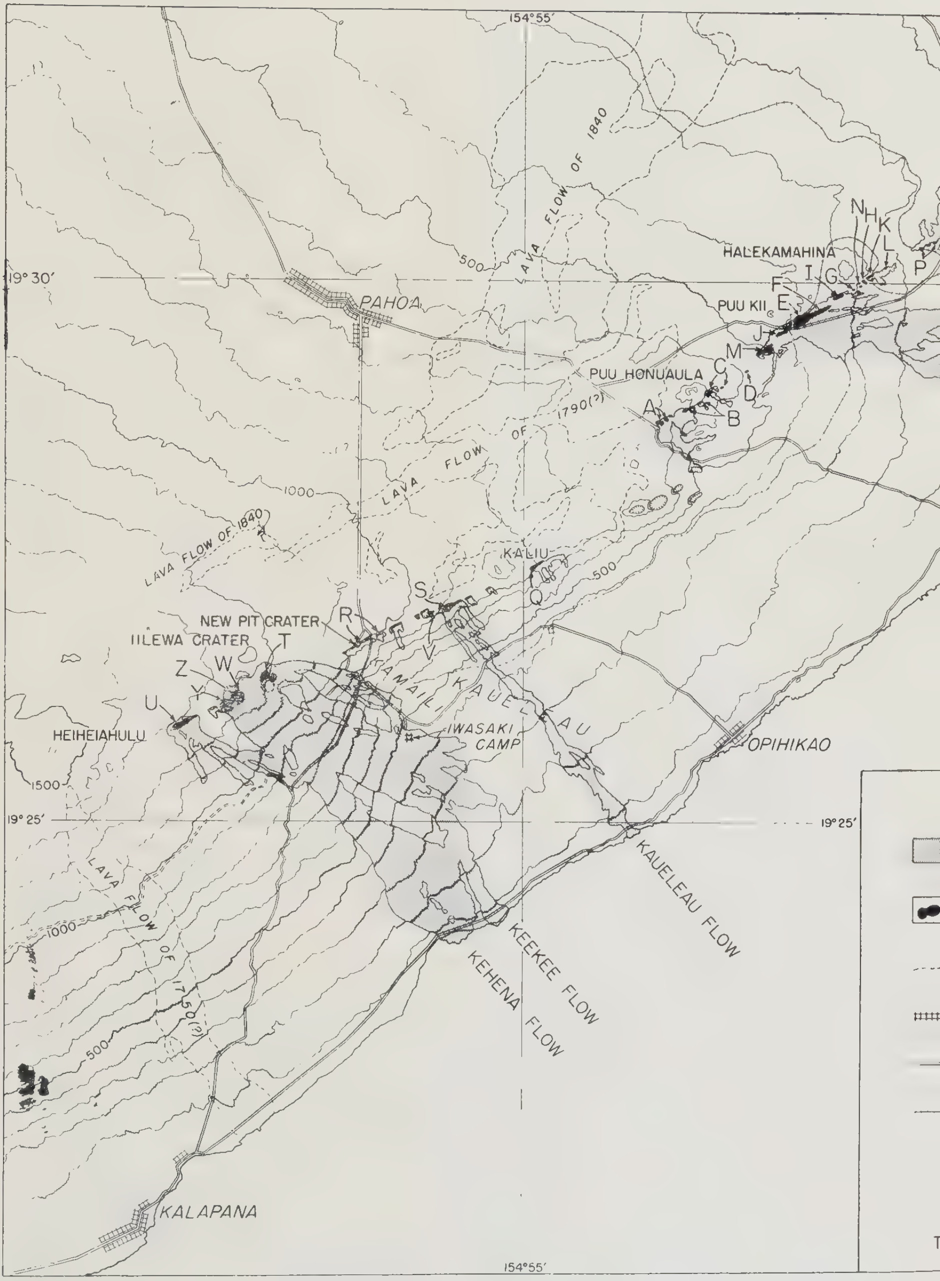

Fig. 12 - Map of the eastern part of the island of Hawaii, show
lava flows and cones of the 1955 eruption of Kilauea.

dogs do not usually behave in that manner during ordinary earthquake swarms.

During the latter half of February horizontal pendulums at the Pahoa station indicated a marked northward tilting of the ground, resulting from a rise of the ground surface along the rift zone to the south. If we assume uniform tilting, and the hinge of the tilting surface to have been at the station, the rise of the surface at the rift zone would have been of the order of 30 cm. This figure corresponds well with the rise farther east on the rift zone, as shown by differential leveling (to be discussed later).

The 1955 eruption of Kilauea
Description of the eruption

First phase. By the evening of February 27 it was evident that volcanic eruption in the region near Pahoa was imminent, although how soon the outbreak would occur was not known. The initial outbreak came at approximately 8:00 on the morning of February 28, at a point (A, fig. 12) 6 km east-southeast of Pahoa.

The eruption can be divided into two distinct phases, that in some respects have the characteristics of two independent eruptions. They will be described in detail elsewhere (MACDONALD and EATON, in prep.), and only a summary of events is given here.

During the morning of February 28 two principal fissures, trending N 65° E, were arranged en echelon with the more easterly fissure offset toward the north. Each was marked by a row, about 100 m long, of lava fountains 1 to 20 m high, and a rather sluggish flow of pahoehoe was spreading around them. Farther northeast (B, fig. 12) were two other short rows of smaller fountains.

The lava fountains in area B declined greatly during the late morning, and by early afternoon only area A remained active. At about 14:00, however, a new group of fountains developed still farther northeast (C, fig. 12). Where the eruptive fissure crossed a road, just west of the end of the

fountain chain in area C, the upper edge of a dike of glowing lava was visible in it 30 to 60 cm below the ground surface, and at intervals of a few seconds to a few minutes bubbles of gas burst through the top of the dike and threw showers of fine incandescent cinder a meter or two into the air. This northeastward extension of the erupting fissures was directly toward the village of Kapoho (fig. 12), and Civil Defense authorities were advised to move people out of that village. By nightfall the evacuation of the village was already well advanced.

About 16:00 activity had resumed in area B. At about the same time it started to decline in area C, and by 16:30 that area was essentially inactive. About 19:30 activity in area C resumed, and spread somewhat both southwestward and northeastward. Activity remained about the same through the rest of the night, though with some fluctuation in the strength of fountaining. By mid-morning of March 1 activity in area C had again ceased. Fountains 15 to 25 m in height in areas A and B had built spatter cones as much as 15 m high.

At 12:15 on March 1 the lava fountains in areas A and B suddenly started to dwindle rapidly, and in 5 minutes had completely disappeared. Immediately, clouds of steam started to issue from the vents in areas B and C, but not in area A. For the most part the escape of steam was gentle, but in the western part of area B and part of area C it rushed forth with sufficient violence to abrade the walls of the vents and carry up a cloud of black sand-sized ash. There was no taste of salt, and very little odor of sulfur gases in the steam clouds. Apparently the steam was simply volatilized ground water. The basal water table in that region lies a few feet above sea level, and the molten lava in the feeding fissures must have withdrawn at least to that depth (180 m) in order to allow large quantities of water to enter the hot fissures and be rapidly volatilized to produce the phreatic eruption. The strong release of steam continued until about 14:30, then gradually diminished through the rest of the afternoon and night.

At approximately 16:00 on March 1 an outbreak of lava occurred on a new fissure at D (fig. 12), 500 m northeast of vent area C. The outbreak lasted only a few minutes, however, and formed a lava flow less than 15 m long.

On the morning of March 2 only a small amount of steam was issuing quietly from the vents in areas B and C, but large numbers of local earthquakes indicated that the eruption was not over. Earthquakes had nearly ceased after the outbreak of lava on the morning of February 28, but on the night of March 1 they were again abundant. Most of the epicenters were further northeast than those of the earlier group.

On the morning of March 2 a crack opened across the Pahoa-Kapoho road, 7 km east of Pahoa (E. fig. 12). At 8:00 this crack was about 2 cm wide, but by 8:30 it had opened to 30 cm. At 11:00 it was 50 to 60 cm wide, and the ground surface southeast of it had been faulted downward about 45 cm in relation to that northwest of it. Other cracks were forming nearby in the same northeast-trending zone, and during the next 3 hours we watched at close range the gradual opening of fissures and formation of fault scarps as much as a meter high. The movement that produced the fault scarps was very slow and gradual. Although dozens of very sharp local earthquakes were felt, we saw no sudden shifts of the faults. At first the movement produced a low monoclinal flexure in the soil or road surface, which gradually grew to a height of 20 or 30 cm. Eventually, however, the monoclines were ruptured and fault scarps produced. Some fault scarps could be followed laterally into still-growing monoclines.

The zone of fissuring expanded in both directions along its strike, and at about 13:00 another similar group of fissures appeared 1.2 km farther to the northeast (N, fig. 12). The fissure zone was following closely the course of a similar zone that developed in 1924 (Jaggar and Finch, 1924), and that extended directly through Kapoho village. Residents

had already been evacuated from the village, but efforts to remove all reasonably movable property were intensified.

At 14:15 lava broke out in area E (fig. 12). The first sign of the actual outbreak was the appearance of wisps of white fume issuing from one of the fissures. These quickly became more numerous and voluminous, until a cloud of dense white sulfurous fume was rising from the opening fissure. Then, less than 5 minutes after the first appearance of fume, small shreds of incandescent lava began to be blown from the fissure, quickly followed by the issuance of liquid lava. Within the next 5 minutes the line of lava fountains had grown northeastward to a length of 300 m, and the largest fountains were shooting to heights of about 15 meters. Very fluid flows of pahoehoe spread outward from the vents at a rate of about 12 m a minute.

During the remainder of March 2 and the early hours of March 3 a series of new vents developed along the fissure zone both northeast and southwest of the point of initial outbreak. At approximately 16:00 the erupting fissure lengthened northeastward to F (fig. 12), increasing the total length of the fountain chain to about 750 m. The fountains were small, ranging in height generally between 3 and 15 m, with occasional bursts reaching 30 m. At 19:25 lava broke out at G, at 19:45 another outbreak occurred at H, at 20:00 still another occurred at I, at 21:00 at J, at 0:35 on March 3 at K, at 2:41 at L (only 0.8 km from Kapoho village), at 3:25 at M, at 5:10 at N. Most of the new vents were short lived. By 6:30 on March 3 the only vents still active were E, J, and M. Flows from those 3 vents had merged to form a single large flow, pahoehoe near the vents, but changing to aa down stream. The front of the flow, about 3 m high and 150 m wide, was advancing 100 m per hour at a point 450 m southeast of vent E. By 12:20 it had reached a point 900 m from vent E.

During the morning of March 3 fountains at vent E increased in height to about 60 m, with occasional scattered bursts of spatter and pumice reaching twice that height. The

fountains at vents J and M ranged from 15 to 30 m high. At 14:45 activity rather suddenly increased, the fountain at vent E reaching heights of 100 to 125 m. By late afternoon the fountain at vent M also was reaching a height of 120 m. The front of the lava flow was 1.6 km from the vents.

About 19:00 new fissures appeared at the western edge of Kapoho village (P, fig. 12), and gradually spread northeastward through the center of the village. Only a police detail, and a few persons still loading heavy appliances and the remainder of store stocks into trucks, still remained in the village, and these were quickly moved away. At approximately 21:30 lava fountains broke out in the western edge of the village. It appeared almost certain that the village would be destroyed. By great good fortune, however, the lava outbreak did not spread into the center of the village, and the flow was turned away from the main part of the village by a low spatter rampart built by a prehistoric eruption. About 15 houses in the outskirts of the village were destroyed by lava, and several others were rendered uninhabitable by the opening of fissures in the ground beneath them, but the main part of the village remained undamaged! By 7:30 on March 4 the lava activity at Kapoho had been replaced by clouds of steam, like those at vents B and C on March 1, and by 8:00 even that activity had ceased. The major lava flow from vents E, J, and M had taken a course south of the big Kapoho tuff cone (fig. 12), and Kapoho village was safe.

On the evening of March 4 the lava flow crossed the coastal road, 4 km from the vents. Through that day the lava fountains at vent E continued to grow, until during the evening the largest fountain was reaching a height of at least 240 m, and a veritable flood of lava was pouring into the head of the flow. During the night of March 4 the rate of outpouring of lava probably exceeded 450,000 cubic meters per hour. By the next day the fountains were smaller, however; and by the morning of March 6 vents J and M were inactive, and the largest fountain at E was only 45 to 60 m

high. By 17:00 the main fountain had ceased entirely, though two lateral fountains, about 8 m high, continued active. Movement of lava from the vents into the head of the flow had nearly ceased, but the front of the flow continued to spread. By daylight on March 7 all activity had ceased at the vents, and the lava flow appeared completely stagnant.

Second phase. Following the new outbreak on March 2 the number of earthquakes declined sharply, until on March 4 there were essentially none. On March 5 earthquakes began again, but this new series of quakes appears to have originated in large part from a portion of the rift zone southwest of the point of the first outbreak on February 28. For several days quakes were recorded on the Pahoa seismograph in great numbers, for periods of several hours averaging two per minute. A spectacular swarm that started at 12:30 on March 5 and continued for 24 hours had its origin at shallow depths near Kalalua Crater, about midway between Kilauea caldera and the site of the February 28 outbreak (Macdonald and Eaton, 1955a, p. 9). Most of the later quakes originated further east, in the vicinity of the road from Pahoa to Kalapana (fig. 12). On March 7 explosion-like noises accompanying small sharp earthquakes were reported on a farm bordering the road 5.5 km south of Pahoa. A dog on the farm behaved in a manner resembling that of the dogs on the Nanawale Ranch in the late days of February. A new outbreak in the general vicinity of the Pahoa-Kalapana road was expected. Finally, on the morning of March 12 cracks appeared in the road at R.

At 17:05 on March 12 lava broke out at Q, and at 19:00 it broke out at S. By midnight, vent Q was inactive, and at daybreak on March 13 the fountains at vent S were very weak.

At 7.50 on March 13 a new outbreak occurred just east of the road at R, and through the day a series of similar small outbreaks took place in the same region (pl. 10-14). These outbreaks occurred in cleared land, or even in the paved road, and afforded us an unparalleled opportunity to observe them in detail at close range.

The following account of the general sequence in the formation of the new vents is quoted from MACDONALD and EATON (1955a, p. 6): « First, hairline cracks opened in the ground, gradually widening to 2 or 3 inches [5 to 7 cm]. Then from the crack there poured out a cloud of white choking sulfur dioxide fume. This was followed a few minutes later by the ejection of scattered tiny fragments of red hot lava, and then the appearance at the surface of a small bulb of viscous molten lava. The bulb gradually swelled to a diameter of 1 to 1.5 feet [30 to 45 cm], and started to spread laterally to form a lava flow. From the top of the bulb there developed a fountain of molten lava which gradually built around itself a cone of solidified spatter ». The outbreak in the road, during the late afternoon, was like the earlier outbreaks except that instead of the lava making its first appearance as a small nearly hemispherical bulb, it pushed up through the pavement as a ridge, 2 or 3 m long and several centimeters thick, gradually increasing in length and thickness, and growing in height to 30 to 45 cm. In actuality, this was the top of a growing dike ! Gas bursting its way through the top of the ridge of lava then started to form a small fountain, which built around itself a cone of welded spatter. By the next morning the cone on the road was 6 m high.

Gradually decreasing activity continued in vent area R until March 17 (pl. 15). At approximately 14:30 on March 14 activity resumed at vent S (pl. 16), and by the morning of March 15 the main lava fountain at that vent was reaching a height of about 120 m. An aa lava flow from the vent advanced southeastward. During the first hour the flow covered a distance of 1.6 km, over a slope averaging about 8°. At the edge of the flow, and as much as 30 m beyond it, there occurred occasional small but violent explosions that threw showers of old rock fragments to distances of 5 or 6 m. These explosions undoubtedly resulted from ignition of hydrocarbon gases, formed by destructive distillation of vegetation buried by the flow, and moving outward through tubes

or fissures in the underlying older rocks (FINCH and MACDONALD, 1953, p. 60). The flow entered the ocean at 5:55 on March 16, having advanced at an average rate of 125 m per hour. Early on the same morning activity ceased at the vent, and by 13:00 the flow was stagnant.

At about 13:00 on March 16 a new outbreak occurred at vent T (fig. 12). By 16:00 the activity had ceased, however. At about 14:30 another new outbreak took place 400 m northeast of vent S, and at 15:50 still another occurred 350 m farther northeast. Small, but vigorous, lava fountains continued active at those points through the night, but ceased during the morning of March 17. At about the same time, activity resumed at vent T. The activity remained rather weak through March 17, but increased rapidly on the afternoon of March 18, with a lava fountain 100 m high and a strong flow of lava moving eastward from it.

At 9:45 on March 19 another outbreak occurred at U (fig. 12). Simultaneously, the activity at vent T decreased greatly, and remained at low ebb for the rest of the day. By 14:15 a row of 5 vigorous lava fountains was playing at vent U, and two lava flows were advancing rapidly southeastward at an average rate of about 260 m per hour. Steam clouds were reported at several places farther west on the rift zone, but no outbreaks of lava occurred there. Activity at vent U continued only until mid-morning of March 20. Concurrently with the decrease of activity at vent U, the fountains at vent T again increased in strength. By evening the main fountain there was about 215 m high, and a voluminous lava flow was pouring southeastward. A broad cone of pumice, cinder, and welded spatter, 300 m across and 30 m high, was gradually built around vent T during the succeeding days. Activity at vent T continued strong until March 25, when it became weak and somewhat intermittent. It ceased altogether on March 27. Again the decline of activity at vent T coincided approximately in time with the beginning of activity at a new vent (W, fig. 12).

Pit craters are numerous on Kilauea and Mauna Loa

volcanoes (MACDONALD, 1956, p. 280-282), but although a few have been known to have formed within historic time, never before had the actual formation of one been observed. At 16:03 on March 20 a sharp explosion in vent area R threw a billowing black cloud to a height of 150 m. Several other, smaller but otherwise similar, explosions occurred during the ensuing hour. No observers were in the area at the time of the first explosion, but a few minutes later aerial inspection revealed a new hole about 8 m across in the ground surface. The walls of the hole diverged downward, and were brightly incandescent. At 17:20 small amounts of black ash were being blown into the air from the crater mouth, and the surface around the crater was covered with a thin layer of black glassy ash and fine cinder. Undoubtedly, this black ash was the cause of the dark color of the explosion cloud. The ash was wholly vitric; no lithic material derived from the old rocks was present. Obviously, the old rocks formerly occupying the volume of the crater had not been blown out by the explosion. They must, therefore, have dropped in. During the next several days many concentric cracks formed around the crater as an area 60 m in diameter slowly sagged toward the crater and sank several decimeters. At night pale flames of burning gas, 5 to 6 m high, could be seen playing over the crater mouth.

There were no signs that lava had overflowed from the crater, or even risen in it to a point near the surface. At first it was not possible to approach close to the crater rim on the ground, and views into the crater from the air were not clear. When, on March 22, a close approach became possible, it was seen that the crater walls consisted of the sharply broken edges of old lava beds, covered in part by a festooned sheet of lava that had dripped and trickled down them. The crater was about 45 m deep. It is difficult to be certain, but it appears probable that the sheet of lava on part of the crater wall resulted from fusion of the wall rocks by the intense heat from burning gases.

At 9:55 on March 25 a new vent developed at V (fig. 12),

and small fountains played briefly at the head of a small lava flow, but by 13:00 the activity had ceased. At 20:00 on March 26 a new outbreak occurred at W, and by 2:00 on March 27 vent T had become inactive. About the same time still another line of lava fountains broke out at Y. A new aa flow from vent W advanced rapidly along the southwest side of the earlier flows from vent T (pl. 17), and at 13:18 on March 28 this flow (Keekee flow, fig. 12) reached the ocean (pl. 18). The average speed of advance of the flow, from the vent to the sea, had been about 150 m per hour for 6 km, mostly through dense forest, down an average slope of 3.5°. In cleared land near the coast the rate of advance was more than twice that, even although the slope of the ground surface was less. Repeatedly, during this eruption, the effect of dense vegetation in slowing down the advance of flows was very conspicuous.

Where the flow entered the ocean, great clouds of steam arose (pl. 18). Along the edge of the steam cloud many black jets were visible (pl. 19). These were so-called « littoral explosions », resulting from water gaining entrance into the hot central part of an aa flow. The violently escaping steam carries with it a cloud of spray, brightly incandescent at night, torn from the central still-fluid portion of the lava. The lava spray chills in the water and air to form black glassy ash and cinder. Some of the black jets of ash-laden steam thus formed attain heights of 15 to 30 m. Individual jets are not instantaneous, but may continue for several minutes (and rarely for many hours). The black glassy sand-sized ash formed in this manner may wash up onto shore to form black sand beaches, and long-continued jets may build cones of cinder and ash, as much as 45 m high, on the flow where it enters the ocean. No such long-lived jets were formed during the 1955 eruption, however.

By the morning of March 29 the Keekee flow had become inactive, but a new flow from vent Y was moving rapidly seaward along its southwestern edge. This flow (Kehena flow, fig. 12) entered the ocean at 18:29 on April 2,

producing the same sort of phenomena previously produced by the Keekee flow (pl. 19). The flow into the ocean continued until April 7, building a promontory of new lava that projected 250 to 300 m beyond the old shoreline.

Early on the morning of March 29 another new outbreak occurred about 300 m southwest of vent Y, but lasted only a few hours. On the morning of March 30 vent T again became active. Vent Y continued strongly active, and vent T moderately to weakly active, until April 2. During April 3 to 5 the fountains at both vents gradually dwindled, and on April 6 they became intermittent. All lava activity ceased during the afternoon of April 7.

For the next two weeks the only activity was light to moderate fume emission at vents T and Y, and steaming at many of the vents farther northeast, especially at vent M. On April 9 a nearly circular hole, about 6 m across, appeared at Z (fig. 12), about 75 m northeast of the base of cone Y. This marked the intersection at the ground surface of a pipe, with brightly incandescent walls, that sloped toward vent Y at an angle of 75°. Gas flames could be seen at night over the entrance of the pipe. On April 10 a bright glow was seen in the crater of cone Y, and loud rumbling sounds were reported from that general area. Loud rumbles were heard again on April 21. During the interval from April 7 to 23 there was a slow slight tumescence of the rift zone in the eruption area, indicated by slight northward tilting at Pahoa. Only a few earthquakes occurred, however, and there were no specific premonitory symptoms of the return of activity. Presumably, the conduits to the surface had remained open.

On April 24 surficial lava activity was resumed, with the advent of weak spattering in the crater of cone T. This appears to have continued for only a few hours, building a spatter conelet about 1 m high, and sending out a lava flow about 15 m long. There was no activity anywhere on April 25.

On the morning of April 26 it was found that aa-type lava had risen in the pipe at Z to within 4 m of the ground

surface. Puffs of sulfurous gas were issuing from a brightly incandescent crack between the wall of the pipe and the new lava plug. At about noon weak spattering was resumed in the crater of cone T, but at a different point from that of the activity of April 24. Again, a spatter conelet and small lava flow were produced. Activity continued intermittently until the morning of April 28. On the afternoon of April 27 lava broke out 200 m east of the cone, and formed a flow of dense, largely degassed pahoehoe that continued until the afternoon of April 28.

On April 29 there was again no activity, but on the morning of April 30 cinder ejection resumed in cone T, and about 11:00 lava broke out at the entrance of the pipe at Z. By 14:45 there were two active vents, about 16 m apart, at Z, pouring out flows of pahoehoe and building cones of spatter. Intermittent moderate to weak spattering continued at vent T until May 5, when it came to a final end. At vent Z activity gradually increased, sending lava flows over the surrounding area to a distance of about 1 km, and building a cone of loose cinder about 25 m high with two small spatter cones just northeast of it. Explosive bursts at the main cone threw showers of ejecta to heights of 30 to 100 m. During this period the activity of the main cone differed markedly from that either before or after it. In place of typical lava fountain activity, it consisted of scattered bursts of discrete cinder, lapilli, and bombs, some of the latter crudely spherical or spindle-shaped, which built a cone of loose material instead of the cones of welded spatter more typical of Hawaiian activity. Simultaneously with the explosive activity in the crater, flows of lava were issuing quietly at the base of the cone. There appears to have been a distinct separation of the liquid and gaseous phases in the vent.

On the morning of May 16 the character of the activity changed abruptly. Both the volume and the fluidity of the escaping lava increased markedly, and the vent activity again became typical lava fountaining. By mid-afternoon a pool of liquid lava 300 m across had formed between cones W and

T, and lava was spilling from the pool southeastward over the heads of the Keekee and Kehena flows. During the next few days a large cone of welded spatter grew around vent Z, completely burying the earlier cone of loose cinder and also the remnants of cone W, which had already been largely overwhelmed by lava flows. By noon of May 17 the lava had risen above the level of the lowest part of the rim of cone T, and was spilling into the crater of that cone; and by mid-afternoon of May 18 the lava had filled the crater of cone T and was spilling out of it toward the east. Overflow continued from the pond southwest of cone T, causing repeated surges of new lava southeastward over the earlier flows to distances of as much as 3 km from the vent. On the afternoon of May 19 one of these surges menaced the Iwasaki Camp (a plantation village), and a warning of danger was issued. The village had already been largely evacuated, but removal of movable property was speeded up. Lava entered and destroyed part of the village at about 21:00, but nearly all the movable property had already been carried to safety.

Similar activity continued until May 25, finally destroying the remainder of the Iwasaki Camp on that day. On May 23 a very spectacular cascade of lava developed at the head of the valley just northwest of cone T (pl. 20). This lava stream, 4 m wide, poured down a slope of about 30° with a speed estimated to be more than 50 km per hour!

This voluminous outpouring of fluid lava, and strong lava fountaining, continued through the morning of May 26. Then suddenly, within 3 or 4 minutes at approximately 11:15, the entire grand display came suddenly to an end. The eruption was over!

The lava flows

The lava flows and cones of the 1955 eruption cover an area of approximately 16 square kilometers. The volume of extruded material is approximately 108 million cubic meters, of which approximately 106 million cubic meters is com-

prised in the lava flows. Near the vents most of the flows were pahoehoe, but more than 0.5 km from the vents they are all aa.

Eight chemical analyses of the 1955 lavas are available elsewhere (MACDONALD, 1955, p. 35; MACDONALD and EATON, in preparation). Mineralogically, the lavas are olivine basalts,

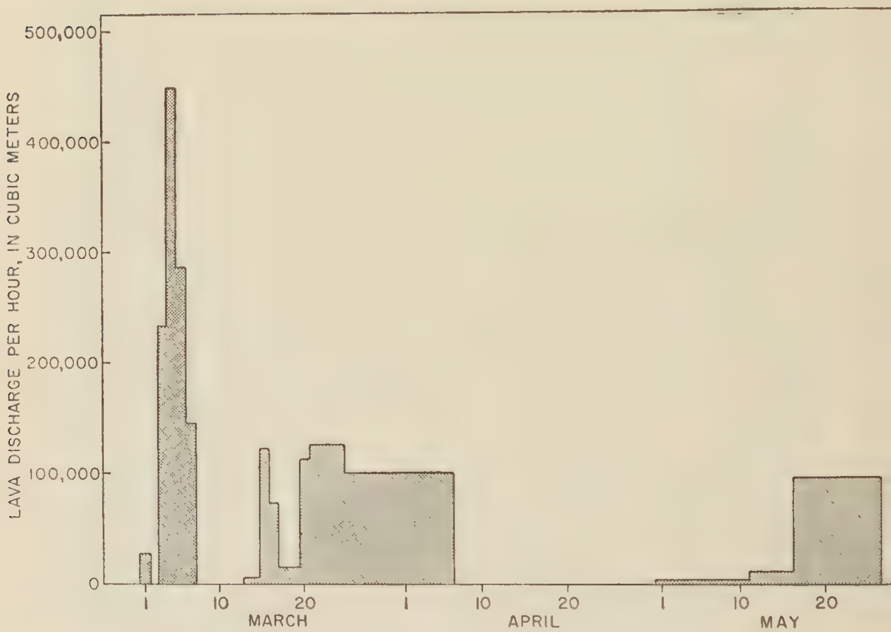

Fig. 13 - Graph showing rate of extrusion of lava during the 1955 eruption of Kilauea.

containing sparse to moderately abundant phenocrysts of olivine, and commonly also phenocrysts of labradorite, in an intergranular to intersertal groundmass of labradorite, monoclinic pyroxene, opaque iron oxides, sometimes a little olivine, and sometimes interstitial glass. All of the analyzed specimens are more than saturated with silica, however, and the olivine phenocrysts show evidence of reaction with the liquid, in the form of rounding and embayment of the crystals. The earliest lavas contain 51.2 percent silica, and were

moderately viscous on eruption. Later lavas contain less silica (the latest of them 50.5 percent), and were much less viscous.

Three pairs of analyses of lava flows just before and after the lava entered the ocean show no changes in chemical composition attributable to entrance of the lava into the sea water.

During the height of the activity, on March 4, the rate of lava extrusion probably exceeded 450,000 cubic meters per hour (fig. 13).

Suitable opportunities to calculate the viscosity of the lavas did not present themselves early in the eruption. On April 6 the viscosity of the feeding river of the Kehena flow, 600 m from its vent, was calculated from the slope, approximate channel dimensions, and speed of flow, to the about 1.6×10^4 poises. Similar calculations for flows during the period from May 9 to 24 yielded values ranging from 2×10^3 poises in a very hot tube near the vent to 2.6×10^4 poises in the feeding channel of a flow 1.3 km from the vent. The viscosities show a very rough correlation with observed or estimated temperature, viscosity decreasing in general with increasing temperature.

Temperature measurements were made with optical pyrometers on both lava fountains and flows. The best measurements, made at vent S on March 15, appear to indicate that the temperature in the core of the fountain was between 1100° and 1120° C (corrected for emissivity and absorption). Temperatures measured in other fountains at other times generally ranged between 1050° and 1080° C (corrected for emissivity), but these are believed to be lower than the actual temperature of the core of the fountain because of the partial screening effect of the cooler ejecta falling around the outside of the fountain. Most of the temperatures measured at close range in active fronts of aa flows ranged from about 920° to 1050° C, but some were as high as 1085°. The very high readings probably are the result of secondary heating of the flow by combustion of hydrocarbon gases derived from vegetation buried by the flow, and probably to a lesser degree

by the liberation of latent heat as crystallization progressed in the flow. Details of the temperature measurements are given elsewhere (MACDONALD and EATON, in preparation).

Ground movements in the eruption area

The eruption was accompanied by a swelling of the eastern part of the east rift zone of Kilauea, producing a rise of the ground surface of approximately 30 cm along the crest of the rift zone arch, a horizontal distension of as much as 1.5 m in the same region, and collapse of a series of grabens along the crest of the arch. A rise of the surface in the vicinity of the rift zone is shown both by northward tilting of the ground at the Pahoa seismograph station, and by leveling surveys before and after the eruption. Horizontal distension is shown by triangulation surveys before and after the eruption, as well as by the visible opening of many fissures. Both the leveling and the triangulation were done along the route of the Pahoa-Kapoho highway by the Highway Department of the Territory of Hawaii.

The drop of the grabens along the rift zone was easily apparent to the unaided eye, and measurements were made by crude hand leveling, in addition to the precise levels mentioned above. Near vent E (fig. 12) the ground surface dropped approximately 1 m. In vent area R it sank about 0.5 m, and between there and vent T it in places sank more than 1 m. The greatest observed drop was at the western edge of Kapoho village. There the graben not only sank, but also tilted southeastward. The exact amount of sinking is uncertain, because the floor of the graben was buried by new lava while the sinking was still in progress, but along the southeastern edge it was more than 1.5 m.

The horizontal and vertical movements in the northeastern part of the eruption area are shown in fig. 14. The vertical changes are referred to a benchmark at the junction of the Pahoa-Kapoho and Pahoa-Pohoiki roads. That benchmark may well also have been elevated somewhat, hence the vertical changes shown are minimal. The gradual rise of

the ground surface as the rift zone is approached is apparent. The triangulation net was not tied to any control outside the eruption area. Therefore all the other stations have been referred to an origin at the Kapoho station, on the prehistoric tuff cone 2.2 km south of Kapoho village. All the horizontal shifts shown are in relation to the Kapoho station. The arrows show the direction of horizontal shift, and the accompanying figures show the amount. It will be seen that at all stations the shift was essentially at right angles to the trend of the zone of eruptive fissures.

Between February 26 and March 13 the ground surface at Pahoa tilted northward through approximately 16 seconds of arc (fig. 15, top). If we assume uniform tilting, with a hinge line at Pahoa, this would indicate a rise of the ground surface along the rift zone to the south, in the vicinity of vent R, of approximately 30 cm. In actuality, since the hinge undoubtedly lay somewhat north of Pahoa, and the amount of uplift probably increased at a rate greater than linear as the rift zone was approached, the total amount of uplift along the rift almost surely was considerably more than 30 cm.

In figures 12 and 16 the en echelon arrangement of the eruptive fissures of 1955 is immediately obvious, as also is the fact that the direction of offset of the fissures in the northeastern area (vents A to P) is opposite to that in the southwestern area (vents Q to U). The obvious interpretation, placed on these facts before the triangulation data became available, was that the fissures were in the nature of gash fractures produced by horizontal displacements of underlying rocks along a fault beneath and approximately parallel to the general trace of the rift zone, the displacement having been right-lateral (northwest side moving northeastward) in the northeastern area, and left-lateral in the southwestern area. This would, of course, demand a reversal of the direction of strike slip between the two major phases of the eruption. Such a reversal of movement appears rather improbable, but is not impossible. J. P. Eaton (personal communication, Nov. 20, 1957) states that a study of first motion

in the earthquakes preceding and during the eruption indicates movement on a fault surface paralleling the surface trace of the rift zone and dipping 70° southeastward. The principal movement was downward in the direction of the dip; however, the seismic data would allow (but do not demand) a smaller right-lateral strike-slip component in the northeastern area, and left-lateral strike-slip component in the southwestern area. (The seismic data will be reported in detail by EATON).

However, the triangulation data (fig. 14) appear to preclude any appreciable strike-slip in the northeastern area, though they permit a downward movement of the block south of the fault. Indeed, a movement of that sort is suggested by the lowering of 35 cm at the benchmark 1600 m west of the Kapoho station. Such a movement parallels the general offset in the Hilina fault system along the southern flank of Kilauea, and that indicated by a buried fault scarp marked by the zone of steep slopes trending northeastward from Kamaili to the Pahoa-Pohoiki road (fig. 12; see also STEARNS and MACDONALD, 1946, pl. 1). The cause of the en echelon arrangement of the eruptive fissures is still unknown.

Events in the caldera area

It has already been stated that the eruption on the east rift zone was preceded by several days of southward tilting of the ground at the northeast edge of the Kilauea caldera. This slow southward tilting, indicating a slight sinking of the caldera floor south of the station, continued through the early part of the eruption. Through that period only the normal number of earthquakes originated in the caldera region.

On March 7 the rate of sinking of the caldera floor became much accelerated, as indicated by rapid tilting toward the center of the caldera. Measurements at stations on both the northeast and west rims of the caldera placed the point of maximum sinking about 1,400 m N 77° E of the center of Halemaumau, at essentially the same location as

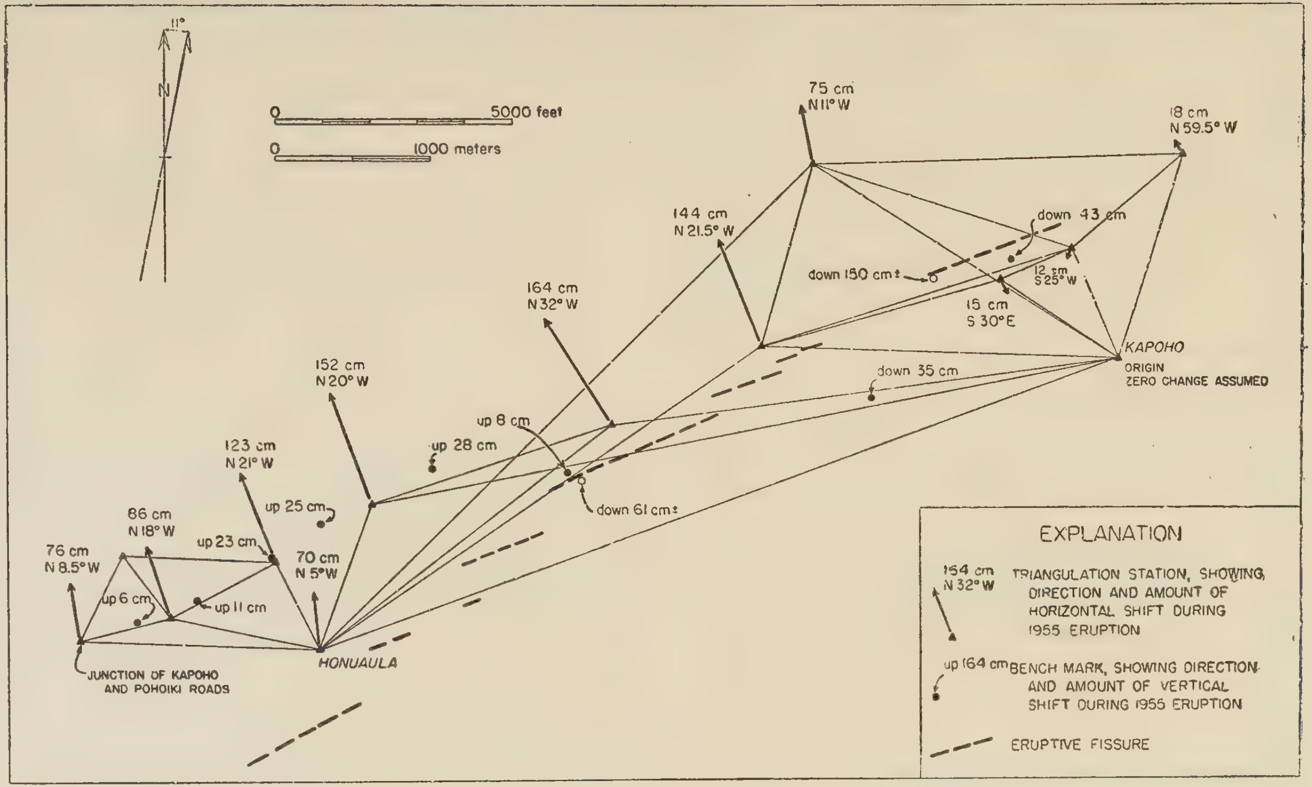

Fig. 14 - Map of the northeastern part of the 1955 eruption area, showing eruptive fissures and direction and amount of movement of the ground surface at various points during the eruption.

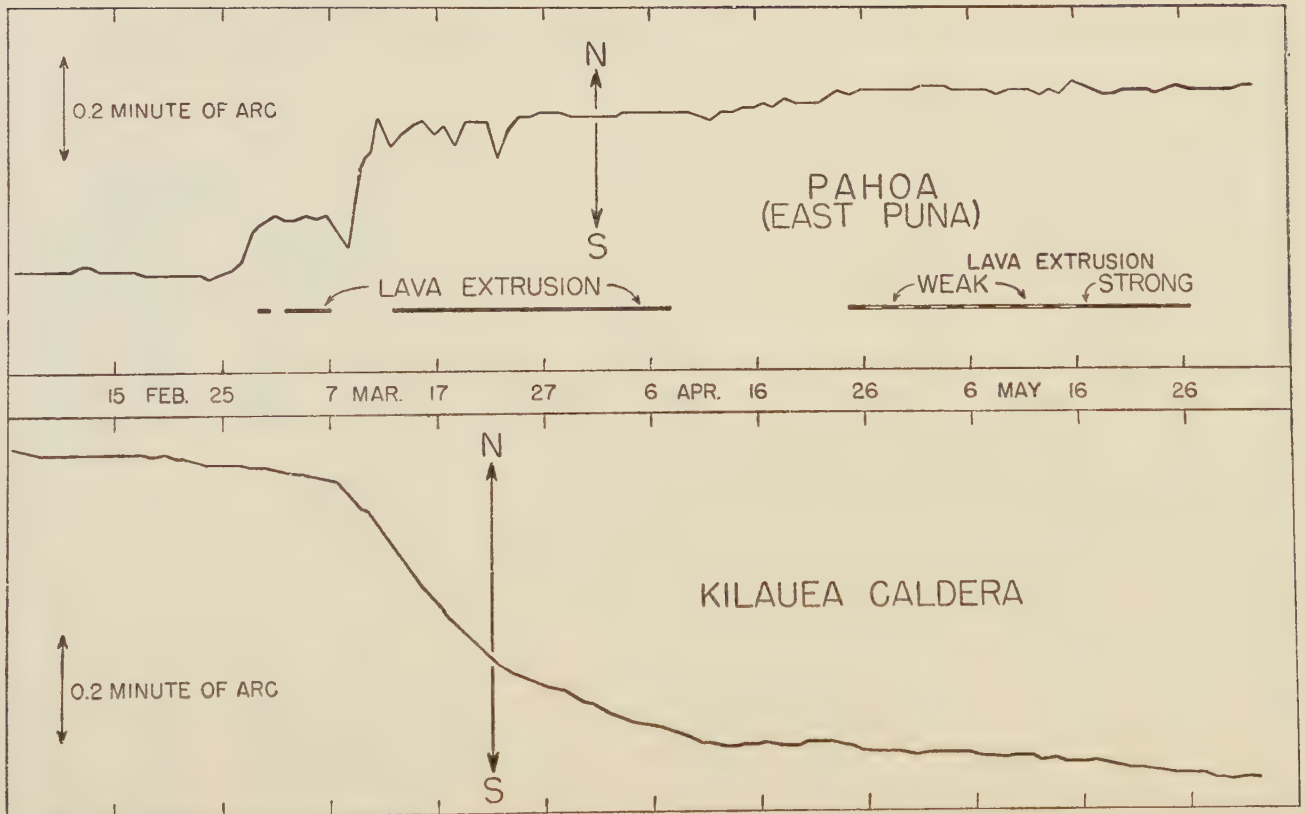

Fig. 15 - Graph showing tilting of the ground surface at Pahoa in the 1955 eruption area, and at the northeastern edge of Kilauea caldera, during the 1955 eruption.

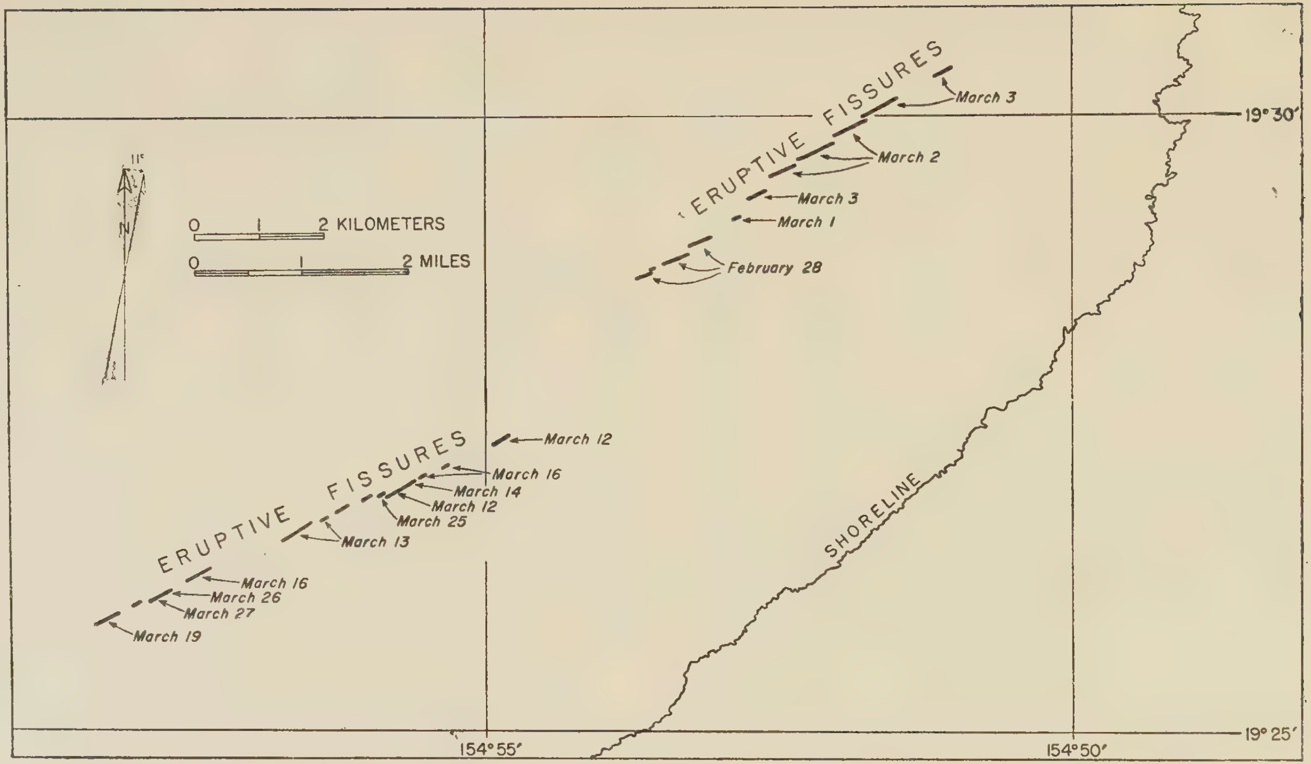

Fig. 16 - Map showing position of the eruptive fissures of 1955, and the order of eruption of the vents.

that during the subsidence of the summit of the volcano in December 1950 (Macdonald, 1954, p. 175). The tilting in the north-south azimuth at the northeast rim of the caldera is shown in the lower part of fig. 15, and in fig. 2. It will be noted that the beginning of rapid sinking in the summit region (best shown in fig. 15) coincided in time with the beginning of the great swarm of earthquakes marking the tearing open of the rift zone that culminated in the new series of lava outbreaks in the southwestern part of the eruption area beginning on March 12. The sinking was accompanied by volcanic tremor, apparently originating at a depth of 10 to 20 km beneath the caldera (J. P. Eaton, in Macdonald and Eaton, 1955a, p. 10), and believed to mark the movement of magma from beneath the caldera into the opening east rift zone.

At first the rapid sinking of the caldera region went on quietly, unaccompanied by any increase in local seismic activity, but by March 12 it appears to have reached a point where abrupt displacements of rock masses, and possibly rupture, started to take place, producing numerous shallow earthquakes. On March 18 alone, several thousand such quakes were recorded. Seismic activity then slowly declined, but with a short intensification marked by more than 2,000 quakes on March 25 and 26. Sinking in the caldera region continued at a decreasing rate through the rest of March and early April. During the period of quiet in the eruption area in mid-April there was no sinking in the caldera region, and in fact a reversal to weak northward tilting suggested a slight reinflation of the volcano. On April 23, the day preceding resumption of eruptive activity, a slow sinking of the caldera floor began again, and continued through the rest of the eruption.

If the hinge line is assumed to be at the stations on the edge of the caldera, and the tilting to be uniform, the area east-northeast of Halemaumau sank approximately 40 cm during the eruption. Actually, the hinge line must have been considerably more remote from the center of subsidence, and

the amount of sinking almost certainly increased at a rate greater than linear as the center was approached, and therefore the maximum sinking must have been considerably more than 40 cm. If we assume it to have been 40 cm, however, and the sinking to have covered about the same area as in 1924 (WILSON, 1935, fig. 8) but to have been everywhere proportionately less in amount, we find the volume of sinking in 1955 to have been approximately 150 million m^3. It is noteworthy that this figure, which should be regarded as only an order of magnitude, is similar to that of the volume of lava extruded in the eruption area. However, the composition of the lavas erupted in 1955 is sufficiently different from that of the lava erupted in the caldera only a few months before, that it appears unlikely that the lava of the 1955 flows was simply drained out from beneath the caldera. It is more probable that instead the magma drained from beneath the caldera replaced at depth that which was actually erupted at the surface.

Conditions at Kilauea and Mauna Loa June 1955 - December 1956

For several weeks after the end of the eruption, on May 26, moderately strong liberation of sulfur fumes continued at vent Z, a subsidiary crater on the northeast side of cone T, and a spot above the fissure zone about half way between vents T and Z. Steaming and light fuming continued at several other vents, and were particularly strong at cracks just southwest of cone M. At the latter point steaming and deposition of native sulfur were still continuing in late 1956, though with lessening intensity.

Through the second half of 1955 there was almost no northward tilting at the northeast rim of Kilauea caldera, during a portion of the year when the ground surface there normally is tilting markedly toward the northeast. This absence of northward tilting indicated a continued slow sinking of the caldera region, negating the effect of the normal seasonal tilting. Subsidence during and following the eruption

has brought the north-south tilt curve (fig. 2) to a level slightly below that preceding the beginning of the tumescence that culminated in the 1952, 1954, and 1955 eruptions. For the most part the volcanoes were seismically quiet during late 1955. On August 9 and 10 about 600 small earthquakes were recorded at the Mauna Loa station, but not at Kilauea. They probably originated on the nearby northeast rift zone of Mauna Loa. On December 12 and 13 a swarm of 200 tiny quakes originated at a depth of about 45 km below Kilauea caldera (J. P. EATON, in MACDONALD and EATON, in preparation).

Northward tilting at the northeast rim of Kilauea caldera in late January, February, and March, 1956, at a season when tilting there normally is southward, indicated that subsidence had come to an end, and slight reinflation of the volcano had begun (MACDONALD and EATON, 1956). Slight tumescence continued through July, but from August to October northward tilting was only about normal, and in November and December southward tilting pointed to a slight sinking of the mountain top (EATON and FRASER, 1956). Eastward tilting at the same station was in excess of normal during the early part of the year, suggesting a slight tumescence of Mauna Loa; but in the second half of the year eastward tilting was less than normal, suggesting that volcanic pressure beneath Mauna Loa was again decreasing. Through most of 1956 seismic activity on the island of Hawaii was less than normal. During July, however, a swarm of tiny earthquakes came from shallow foci in or near Kilauea caldera (EATON and FRASER, 1956). The year 1956 closed with both Kilauea and Mauna Loa quiet, and with no indications of coming eruptive activity.

Probable submarine eruptions in 1955 and 1956

On August 20, 1955, persons aboard a plane en route from Tokyo to Honolulu sighted a disturbance in the ocean at 23° 35′ N., 163° 50′ W., approximately 90 km N 85° E of Necker Island, in the northwestern part of the Hawaiian Archipelago (fig. 17). Their attention was first called to the

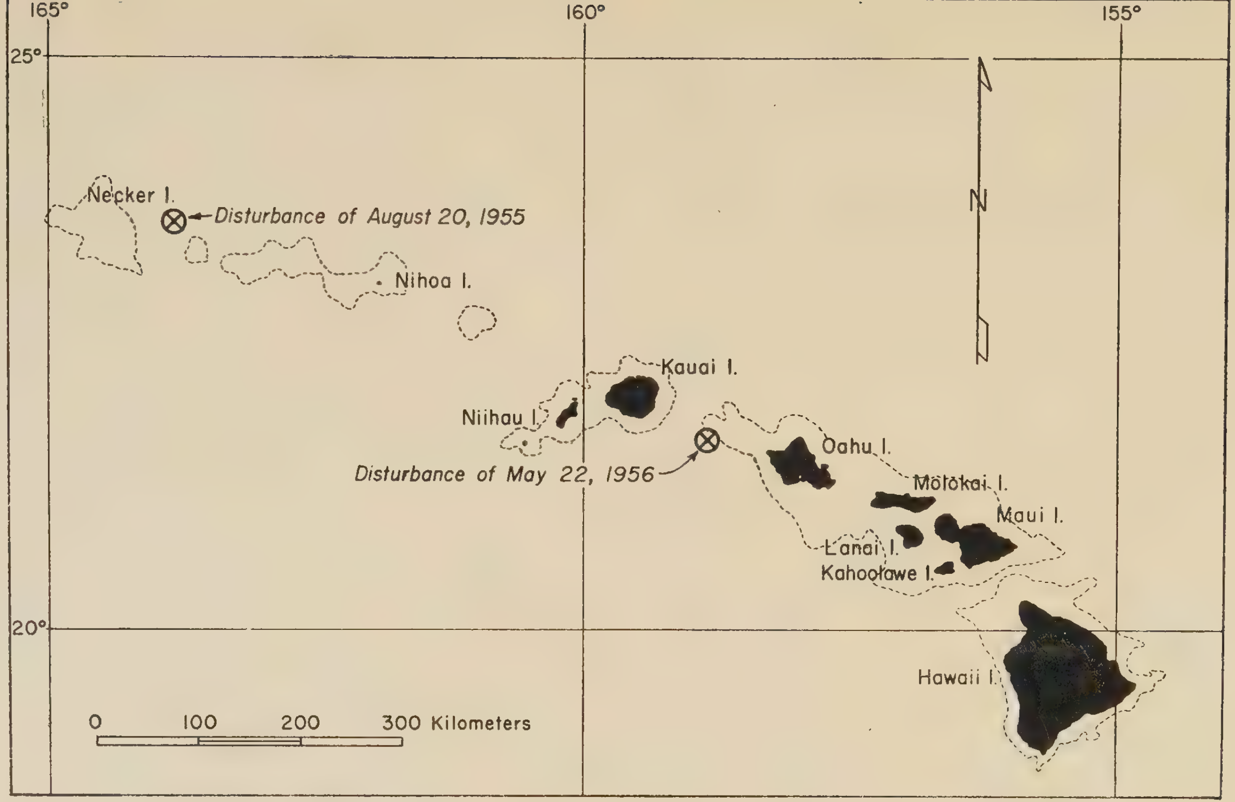

Fig. 17 - Map of the southeastern end of the Hawaiian Archipelago, showing the location of undersea disturbances during 1955 and 1956. The dashed line represents the 1,000-fathom (minus 1,829 m.) contour.

phenomenon by a column of « smoke » (probably steam) rising several thousand meters into the air. On closer approach they saw an oval patch of steaming turbulent water, about 1.5 km across, surrounded by a thin line of yellowish surf, with yellowish water drifting away from it. Near one end of the oval was an area of several thousand square meters of what looked like dry land. The latter probably was a raft of floating pumice, which quickly became water-logged and sank. By the next day, when other planes visited the area, there were no further signs of disturbance other than a slick appearance of the water surface in the formerly turbulent area and a series of long swells sweeping outward from it. These swells were reported to be identifiable nearly to the island of Kauai.

There appears to be little doubt that the disturbance was caused by a submarine eruption. The point lies just north of the Hawaiian Ridge, as shown on maritime charts, in a depth of nearly 4,000 m. No other volcanic activity has been reported in the northwestern part of the Hawaiian Archipelago, but until very recently the area has been visited very infrequently, and brief activity could easily have escaped observation.

On May 22, 1956, a disturbance of more dubious origin took place in the Kauai Channel, between the islands of Kauai and Oahu, in the main Hawaiian group. About 13:15 the crew of a U. S. Navy plane observed a patch of brownish-yellow material, about 0.4 km across, in the water about 60 km N 80° W of the westernmost point on Oahu. The point is on the south side of the submarine ridge connecting the two islands, in a depth of water of nearly 3,000 m. At low altitude the crew members could smell a sulfurous odor, but could detect no smoke or steam, nor could they see any bubbling or turbulence in the water. At 14:00 another plane reported conditions unchanged, but the pilot could not detect any odor of sulfur gases. At 15:25 and 16:00 conditions were the same. Lt. Cdr. Claude Briggs, pilot of the first plane, stated that the activity closely resembled that he

had seen near Necker Island on August 20, 1955, except that there was no « smoke » cloud. Lt. F. L. Moody, pilot of the second plane, had observed the eruption at Didicas Rocks, north of Luzon Island in the Philippines, in 1952, and stated that the activity between Oahu and Kauai resembled that at Didicas Rocks before the latter reached the surface of the ocean. A newspaper representative reported boiling water and steam in the area about 16:00, but others in the same plane observed neither.

Early the next day the material in the water had been drawn out into a streak about 50 m wide and several kilometers long. Later, however, a new mass of material was reported. A pilot who had flown repeatedly in the area of the 1955 eruption of Kilauea reported the smell of sulfurous eruption gases over the patch in the ocean. D. A. Davis, geologist of the U. S. Geological Survey, D. C. Cox, geologist of the Hawaiian Sugar Planters' Association, and A. T. Abbott, professor of geology at the University of Hawaii, reported seeing fragments 5 to 10 cm in diameter floating in the water, while they were flying over at very low altitude, but smelled no sulfur gas. William Pell, of Honolulu, reported two distinct area of discoloration, about 15 km apart. Roger Coryell, of Honolulu, took moving pictures that confirmed the general description of the discolored area and showed distinct, though not violent, physical disturbance in the water. A plane pilot reported sighting two dead whales floating in the disturbed area. This was confirmed by the captain of a fishing boat that had passed through the area, who stated that the bodies of the animals appeared to be undamaged and suggested that they had been poisoned. The same captain reported brownish-black fragments resembling cinder, several centimeters in diameter, floating in the water. He stated that he actually picked up some of the material, but unfortunately threw it back into the water. On May 24 the discolored water was seen from the air to be rapidly dissipating, and a search by boat revealed nothing.

On May 28 Michael and Robert Bell found pieces of

pumice on the beach at Lanikai, on the northeast side of the island of Oahu, and on the same day Kiyoshi TAKASAKI, geologist of the U. S. Geological Survey, found similar fragments at Kahana Bay, 25 km farther northwest. The pumice was dark brown to black basaltic pumice, containing phenocrysts of olivine and labradorite. The fragments were fresh and uneroded, and tests revealed that they would float for only a few hours. Surface currents are ordinarily not favorable to bring material from the disturbed area to the northeast coast of Oahu, but any other source for the pumice is difficult to visualize.

Several other areas of discolored ocean water in the Hawaiian area have since been shown to be caused by sudden prolific flowering of algae, and it has been contended that the disturbance in the Kauai Channel was of the same origin. In support, the fact is cited that sensitive seismographs at the Honolulu Magnetic Observatory recorded neither harmonic tremor nor nearby earthquakes during the period of the disturbance. However, the seismograph station is more than 90 km from the disturbed area, and it is well known that earthquakes accompanying volcanic eruptions commonly are recorded only within a few kilometers of the erupting vent. A definite assertion is not possible, but the evidence appears to me to indicate a submarine eruption.

REFERENCES CITED

BRIGHAM, W. T., 1909 - *The volcanoes of Kilauea and Mauna Loa:* B. P. Bishop Mus. Mem., vol. 2, no. 4, 222 pp., Honolulu.

DANA, J. D., 1890 - *Characteristics of volcanoes.* 399 pp., New York.

EATON, J. P., and FRASER, G. D., 1956 - Hawaiian Volcano Observatory Summary 3, July-September 1956, p. 1-5; Summary 4, October-December 1956, p. 1-5; U. S. Geol. Survey, Washington, D. C.

ELLIS, William, 1827 - *Narrative of a tour through Hawaii....* 442 pp., London; reprinted Honolulu, 1917.

FINCH, R. H., 1940 - *Engulfment at Kilauea volcano:* Volcano Letter, no. 470, p. 1-2.

——— 1941 - *The fiilling in of Kilauea crater:* Volcano Letter, no. 471, p. 1-3.

———— 1943 - *The seismic prelude to the 1942 eruption of Mauna Loa:* Seismol. Soc. America Bull., vol. 33, p. 237-241.

———— 1944 - *The November-December 1944 crisis at Kilauea:* Volcano Letter, no. 486, p. 1-2.

———— 1950 - *The December 1950 subsidence at Kilauea:* Volcano Letter, no. 510, p. 1-3.

Finch, R. H., and Macdonald, G. A., 1953 - *Hawaiian volcanoes during 1950:* U. S. Geol. Survey, Bull. 996-B, p. 27-89.

Hitchcock, C. H., 1909 - *Hawaii and its volcanoes*, 314 pp. Honolulu.

Jaggar, T. A., 1934 - *Kilauea's lost lava flow:* Paradise of the Pacific, vol. 46, no. 6, p. 5-9.

Jaggar, T. A., and Finch, R. H., 1924 - *The explosive eruption of Kilauea in Hawaii, 1924:* Am. Jour. Sci., 5th ser., vol 8, p. 353-374.

Macdonald, G. A., 1952 - *The south Hawaii earthquakes of March and April, 1952:* Volcano Letter, no. 515, p. 1-5.

———— 1954 - *Activity of Hawaiian volcanoes during the years 1940-1950:* Bull. volcanologique, sér. 2, vol. 15, p. 119-179.

———— 1955 - *Catalogue of the active volcanoes of the world including solfatara fields. Part III, Hawaiian Islands.* 37 pp., Naples.

———— 1955 a - *Hawaiian volcanoes during 1952:* U. S. Geol. Survey, Bull. 1021-B, p. 15-108.

———— 1956 - *The structure of Hawaiian volcanoes:* Verh. Kon. Nederlandsch. Geol. Mijnb. Genoots., vol. 16, p. 274-295.

Macdonald, G. A., and Eaton, J. P., 1954 - *The eruption of Kilauea volcano in May, 1954:* Volcano Letter, no. 524, p. 1-9.

———— 1955 - *Hawaiian volcanoes during 1953:* U. S. Geol. Survey, Bull. 1021-D, p. 127-166.

———— 1955 a - *The 1955 eruption of Kilauea volcano:* Volcano Letter, no. 529-530, p. 1-10.

———— 1956 - Hawaiian Volcano Observatory Summary 1, January-March 1956, p. 1-5; Summary 2, April-June 1956, p. 1-5: U. S. Geol. Survey. (This publication replaced the data section of the Volcano Letter, publication of which was terminated with the July-December 1955 issue).

———— 1957 - *Hawaiian volcanoes during 1954:* U. S. Geol. Survey, Bull. 1061-B, p. 17-72.

———— in preparation. *Hawaiian volcanoes during 1955:* U. S. Geol. Survey, Bull.

Macdonald, G. A., and Wentworth, C. K., 1952 - *The Kona earthquake of August 21, 1951, and its aftershocks:* Pacific Science, vol. 6, p. 269-287.

———— 1954 - *Hawaiian volcanoes during 1951 :* U. S. Geol. Survey, Bull. 996-D, p. 141-216.

Stearns, H. T., and Macdonald, G. A., 1946 - *Geology and ground-water resources of the island of Hawaii:* Hawaii Div. of Hydrography, Bull. 9, 363 pp., Honolulu.

Wilson, R. M., 1935 - *Ground surface movements at Kilauea volcano, Hawaii:* Univ. Hawaii, Research Pub. 10, 56 pp.

Yokoyama, I., 1957 - *Energetics in active volcanoes, 2nd paper:* Earthquake Research Institute, Tokyo Univ., Bull., vol. 35, pt. 1, p. 75-97.

PLATES

Plate 1. - Lava fountains along the fissure across the southwest part of the floor of Halemaumau crater at 2:15 on June 28, 1952. The large fountain at the left-hand edge is the big southwestern fountain, which had decreased from its maximum size to a height of 45 meters.

Plate 2. - The lake of liquid lava and the fountain at the southwest edge of Halemaumau at 7:20 on June 28, 1952. The fountain is about 15 m high. Waves are visible in the lake, spreading outward from the fountain.

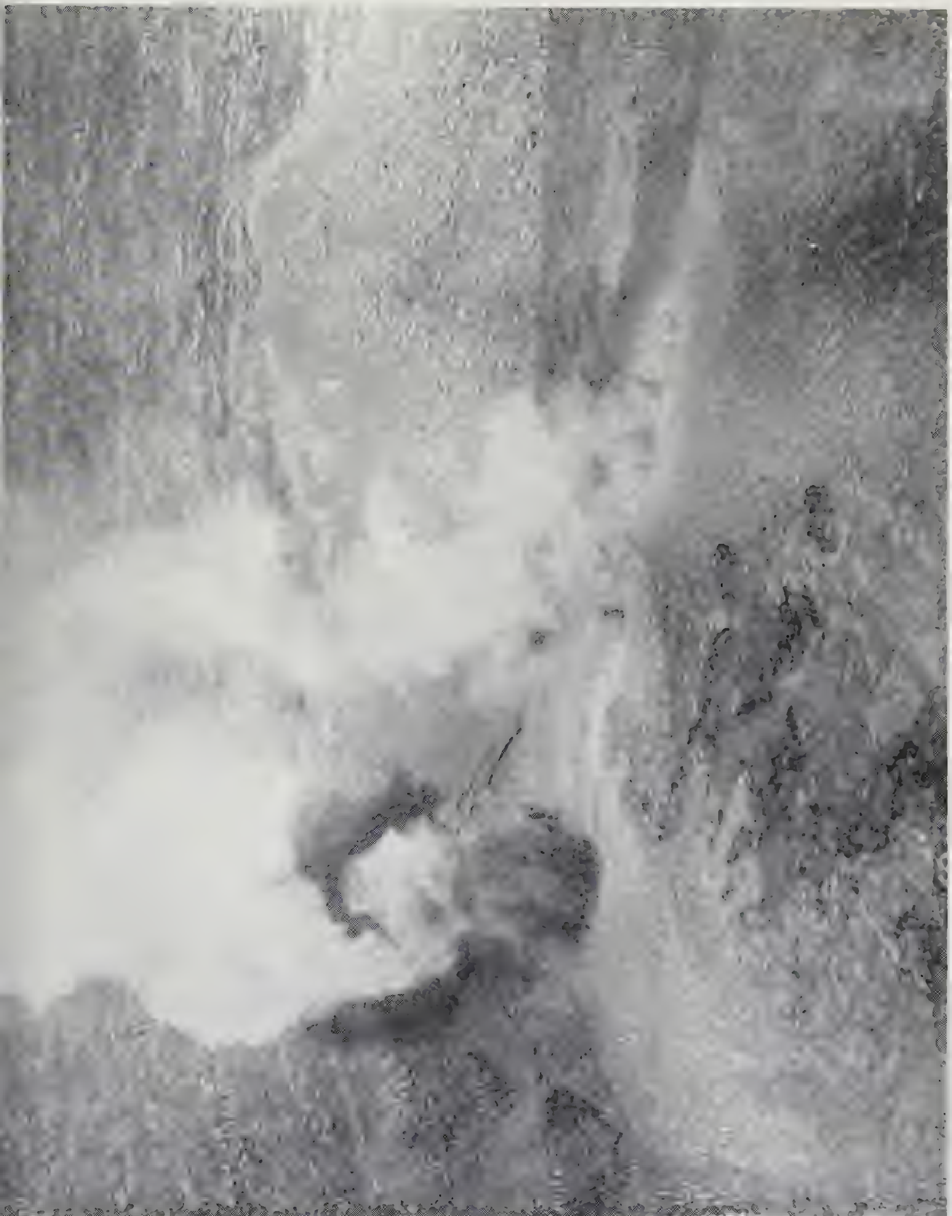

Plate 1. Lava fountain 45 m high at the southwest edge of Halemaumau at 11:05, July 2, 1952. A row of smaller fountains lies farther to the right (northeast).

Plate 4. - View southwestward across the lava lake in Halemaumau, July 29, 1952. Lava rivers are pouring out through gaps in the cone walls to feed the surrounding lava lake. In the foreground the lava ring holds the surface of the lake 12 m above the surface of the adjacent « bench » lava that forms the main crater floor.

Fig. 5. - View northwestward across the southern part of Halemaumau crater on August 12, 1952. The highest points on the cone are about 20 m above the surrounding crater floor. On the east and south sides lava rivers issue from the cone and feed the surrounding lava lake.

Plate 6. - Small lava lake, overflowing southward and northeastward, on September 20, 1952, seen from the southeast. The lake is about 35 m across.

Plate 7. - Lava fountains along the fissure northeast of Halemaumau, and the lava flow spreading out from them, seen from the Volcano Obsservatory about 6.00 o' clock on May 31, 1954. At the right a fume cloud rises from Halemaumau, and the top of a big lava fountain is barely visible in the fume.

Photo by R. T. Kanemori. Modern Camera Center. Hilo.

Plate 8. - Lava cascade on the northeast wall of Halemaumau, and fountain at its foot, at 6:30 on May 31, 1954. The cascade is 120 m high.

Photo by R. T. KANEMORI.

Plate 9. - View southwestward across Halemaumau at 6:30, May 31, 1954. A large fountain, 40 m high, is playing at the foot of the southwest wall of the crater, and another on the right near the middle of the crater. A row of small primary fountains lies between them, and other rows lie just to the northwest. Many small secondary fountains and bright cracks are visible on the lake surface.

Photo by R. T. KANEMORI.

Plate 10. - Fume just starting to issue from a newly opened fissure in the soil in vent area R (figure 12) at about 13:40 on March 13, 1955. This was the beginning of formation of a new vent. Lava reached the surface here a few minutes later.

Plate 11. - Fume pouring from the same fissure shown in plate 10, at about 13:50 on March 13.

Plate 12. - Lava reaching the surface on the fissure shown in plates 10 and 11, at about 14:00 on March 13. A mound of lava 15 cm high is visible in the center of the picture, and shreds of spatter can be seen in the air above it.

Plate 13. - A later stage in the development of the new vent shown in plate 12, at 14:03 on March 13. The mound of lava is about 30 cm high.

Plate 14. - The same vent shown in plate 13, about 10 minutes later. The mound in the center has grown to a height of about 1 meter, and the intensity of the spattering has increased.

Plate 15. - Spatter cone 3 m high, in vent area R (fig. 12) on the morning of March 14, 1955.

Plate 16. - Lava fountain 50 m high, in vent area S (fig. 12) on the afternoon of March 14. A cinder-and-spatter cone is just starting to grow at the base of the fountain.

Plate 17. - Front of an aa lava flow, 3 to 4 m high, advancing across cleared land near the coast at noon on March 28, 1955. The flow was advancing about 330 m per hour. Flames along the edge of the flow are from burning vegetation.

Plate 18. - Lava flow pouring over a sea cliff, 15 m high, into the ocean at 13:25, March 28, 1955. Clouds of steam rise from the boiling water at the foot of the cliff.

Plate 19. - The steaming terminus of the Kehena lava flow (fig. 12) in the ocean, about 10:30 on April 3, 1955. The flow had built a promontory that extended 240 m beyond the old shore line. In front of the white steam cloud a littoral explosion is throwing up a black jet of ash-laden steam.

Plate 20. - Lava river, 4 meters wide, pouring down a slope of about 30° just northeast of vent 7 (fig. 19) on the afternoon of May 24, 1955. The speed of flow in the river was estimated to be more than 60 km per hour.

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Geology of the Islas Revillagigedo, Mexico

1. Birth and development of Volcán Bárcena, Isla San Benedicto (1)

(With 5 text-figures and 28 plates)

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Abstract

On August 1, 1952, a new volcano named Bárcena was born on Isla San Benedicto, which is located about 300 nautical miles off the west coast of Mexico. A pyroclastic cone nearly 1100 feet above sea level was formed by August 2. By mid-September cone formation had ceased and a small lava plug capped the magma conduit in the crater. After a period of quiescence from mid-September until early November activity resumed and blocky, soda trachyte lava formed two domes in Bárcena crater during November and early December. On December 8 lava flowed through the base of the volcano and formed a delta nearly one-half mile out to sea by the end of February, 1953. All activity, except solfataric steaming, stopped by this date.

Volcanic density flows (« *nuées ardentes* ») descended the cone during the period of cone formation. As the expulsion of ash and steam decreased in early September, 1952, the

exterior of the cone is believed to have been furrowed by these avalanches. Volcán Bárcena has an index of explosiveness of about 90 per cent, the highest of any known oceanic volcano in the eastern Pacific Ocean. Calculations indicate that about 10,500 million cubic feet (300 million cubic meters) of tephra and lava were erupted during the life of Bárcena.

Introduction

General statement and location.

There are few volcanoes whose birth and development have been witnessed by man. In the western hemisphere the life of the only new volcano studied in detail, prior to the birth of Volcán Bárcena, was Parícutin (Foshag and González R., 1956). Unlike Parícutin, which was under almost continuous surveillance, Bárcena was visited only occasionally for periods of a few hours to a few days during its brief period of activity. Yet, apparently without exception and despite the remote location, observers fortuitously were present at all crucial periods of the volcano's development including its birth. The eruption of Bárcena is especially significant because it is the first recorded historic pumice eruption in the eastern Pacific Ocean basin (Williams, 1952).

Volcán Bárcena is located on the southern part of Isla San Benedicto, which is the third largest and most northeastern of the four Islas Revillagigedo of Mexico (Fig. 1). The island is located about 220 nautical miles south of Cabo San Lucas, Baja California, and nearly 300 miles west of Cabo Corrientes on the Mexican mainland.

This paper is the first of a proposed series of papers which will deal with the terrestrial and submarine geology of the individual Islas Revillagigedo and adjacent area.

Previous investigations and literature.

The initial study of Bárcena through October, 1952, was made by Dr. Robert S. Dietz, who conducted the first scientific investigation of the new volcano on two flights to Isla

San Benedicto in September, 1952 (Dietz, 1953). Prof. Howel Williams, who was on the second flight, prepared a geol-

Fig. 1. - Location of the Islas Revillagigedo.

ogical sketch map of San Benedicto during the time the plane circled the island and later wrote a brief statement on the early activity (Williams, 1952).

A preliminary account of the development of Bárcena was prepared in 1953 by Richards and Dietz (1956). Additional brief reports on particular phases of the early activity of the volcano were written by Dietz and Richards (1953), Richards (1953), and Richards and Walker (1954). The present paper represents part of the writer's Ph. D. dissertation, « Geology, volcanology, and bathymetry of Isla San Benedicto, Mexico », submitted to the University of California, Los Angeles, in 1957.

An investigation of sounds made by the erupting volcano was made by Snodgrass and Richards (1956) from November, 1952, to May, 1955. Richards (1958) reported on a trans-Pacific drift of floating San Benedicto pumice which originated from the eruption and was collected on Hawaii, Johnston, Wake, and the Marshall Islands. The pumice is believed to have reached the Palau Islands, which are located in the western Pacific Ocean.

Fieldwork.

Five visits by sea were made to Isla San Benedicto from 1952 to 1957 (Table 1). On these visits a total of ten days were spent on land and five days at sea. Ten U. S. Navy photographic and observation flights to San Benedicto were planned by the writer with the help of the photographic officers of Photographic Squadron Sixty-one, Utility Squadron Seven, and Patrol Squadron Forty-six from November, 1952, to January, 1956. He participated on seven of them.

The majority of observations of Volcán Bárcena during the period of cone building and lava extrusion were made by men of the California tuna fishing fleet.

Names of geographic features.

Prior to the birth of Bárcena the only names of geographic features in general use were the following: Ash Heap (Montículo Cinerítico), Herrera Crater, White Bluffs, and Black Bluff. The latter two names are no longer applicable

Table 1.

Observations of Volcán Bárcena: 1952 - 1957.

Date	Observer (1)	Ship or airplane
1952		
August 1	J. da Luz R. Petrie F. Rodriques	Tuna clipper M/V *Challenger*
August 12	C. Blasko T. Howell	Tuna clipper M/V *Intrepid* and its seaplane
September 12	G. Anderson R. S. Dietz R. H. Finch	U. S. Air Force B29, 55th Strategic Reconnaissance Squadron
September 20	E. Boldrick R. S. Dietz H. Williams	U. S. Air Force B29, 55th Strategic Reconnaissance Squadron
November 12-15	M. Neves, Jr.	Tuna clipper M/V *Constitution*
November 15	D. L. Inman A. F. Richards J. M. Snodgrass	U. S. Navy PBM, Squadron VU-7
November 16-17	R. Madruga	Tuna clipper M/V *American Ladies*
November 19	J. Madruga G. Zeluff	Tuna clipper M/V *Paramount*
December 4, 7-9	E. Perriera M. A. Silva	Tuna clipper M/V *Star of the Sea*
December 7-9	J. da Luz	Tuna clipper M/V *Challenger*
December 8	C. Marino	Tuna clipper M/V *Santa Margarita*
December 9	G. Zeluff	Tuna clipper M/V *Paramount*
December 9-12	N. C. Bunker, in charge	Yacht *Observer*
December 11	A. F. Richards V. Silva	Seaplane of the M/V *Southern Queen*
December 13	J. Zolezzi	Tuna clipper M/V *St. Mary*
December 13	J. Canepa	Tuna clipper M/V *Shasta*
1953		
January 4-5, 12	J. Baker P. Lynn	Tuna clipper M/V *Cape Beverly*
February 27	E. Mitchell R. H. Morton	Tuna clipper M/V *Columbus*

(1) Where more than three persons participated on a trip only the person in charge is listed.

Table 1 (continued)

Date	Observer	Ship or airplane
March 9-13, 28	B. H. Brattstrom H. Dana A. F. Richards	R/V *Paolina T*, Scripps Institution of Oceanography
circa March 23	V. Silva	Seaplane of the M/V *Southern Queen*
April 16	W. Bascom A. F. Richards J. M. Snodgrass	U. S. Navy P4Y-1P, Squadron VJ-61
May 20	R. MacAllister A. F. Richards J. M. Snodgrass	U. S. Navy P4Y-1P, Squadron VJ-61
July 13	A. F. Richards J. M. Snodgrass	U. S. Navy P4Y-1P, Squadron VJ-61
September 21	S. D. Hinton A. F. Richards J. M. Snodgrass	U. S. Navy P4Y-1P, Squadron VJ-61
November 17-20	A. F. Richards, in charge	R/V *Crest*, Scripps Institution of Oceanography
1954		
August 6	(photographic flight only)	U. S. Navy AJ-2P, Squadron VJ-61
October 28	B. H. Brattstrom H. L. Mason A. F. Richards	U. S. Navy P4Y-1P, Squadron VJ-61
1955		
March 25	J. H. Cawley A. F. Richards	U. S. Navy P5M, Squadron VP-46
May 1-5	A. F. Richards, in charge	R/V *Crest*, Scripps Institution of Oceanography
May 27	(photographic flight only)	U. S. Navy AJ-2P, Squadron VJ-61
1956		
January 26	(photographic flight only)	U. S. Navy AJ-2P, Squadron VJ-61
1957		
March 18	A. F. Richards, in charge	R/V *Stranger*, Scripps Institution of Oceanography

because the features were obliterated during or shortly after the eruption.

In September, 1952, Prof. Howel WILLIAMS suggested the name Boquerón, meaning Big Mouth, for the new volcano (DIETZ, 1953, p. 26). Boquerón Crater was formally proposed in a letter written in October, 1952, by Dr. DIETZ to the Mexican Ambassador in Washington, D. C. In July, 1953, an answer was received that the Department of Agriculture of the Mexican Government and the Geological Institute of the National University had proposed the name of the distinguished Mexican geologist Mariano BÁRCENA for the new volcano following a suggestion of the late Ing. Teodoro FLORES, Director of the Instituto de Geología (Carl FRIES, Jr., personal communication). Volcán Bárcena is preferable to Boquerón and has been adopted; a volcano named Boquerón is located in the Mexican State of Chiapas (SAPPER, 1937, p. 11).

The new names used in Figure 2 were proposed by the writer and translated from English into Spanish by Dr. FRIES. Their etymology is described by RICHARDS and BRATTSTROM (1959).

Acknowledgments.

I acknowledge my gratitude to the numerous people who have assisted me in the field, donated photographs, and discussed various aspects of this study. Unfortunately space does not permit individual recognition. I particularly wish to thank all of the cooperative and friendly tuna fishermen whose contribution to the understanding of this volcano cannot be over emphasized.

Mr. Lewis WAYNE WALKER, my companion on the December, 1952, visit, earned by admiration for his photographic ability and cheerfulness in the field. He personally supplied considerable quantities of film so that a complete record of Bárcena's activity could be obtained.

The trip from California to Isla San Benedicto in December, 1952, was made possible by Mr. Woodrow KRIEGER,

co-owner of the yacht *Observer*, and Dr. Bruce HALSTEAD,

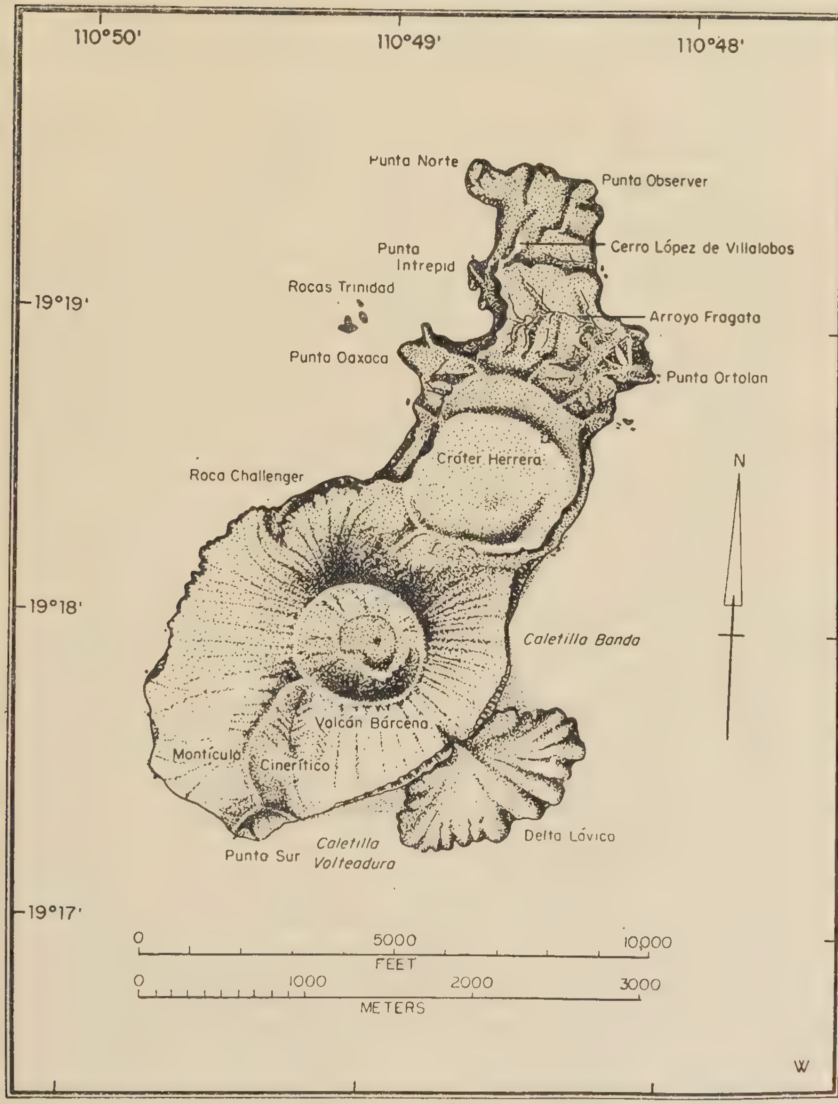

Fig. 2. - Map of Isla San Benedicto.

who was in charge of the Galápagos expedition of the School of Tropical and Preventive Medicine, College of Medical

Evangelists. Captain Erlin Perriera, M/V *Star of the Sea*, and Captain Frank Valin, Jr., M/V *Columbia*, befriended and transported us when hitch-hiking by tuna clipper back to California from San Benedicto.

Captains Robert C. Newbegin, Laurence E. Davis, and Robert B. Haines, officers, and crew of the Scripps Institution of Oceanography's Research Vessels *Paolina T*, *Crest*, and *Stranger* worked long hours and cooperated in every way on the cruises to the Islas Revillagigedo in 1953, 1955, and 1957.

The Office of Naval Research sponsored all of the flights to Isla San Benedicto between 1953 and 1956. I express my appreciation to the officers and men of the U. S. Navy Utility Squadron Seven, Patrol Squadron Forty-six, and, particularly, Photographic Squadron Sixty-one, which flew eight completed missions, for their cooperation and willingness to help, at times under adverse conditions and personal danger.

I am very grateful to Dr. Robert S. Dietz of the U. S. Navy Electronics Laboratory in San Diego for early guidance, continued encouragement, and for the use of his unpublished reports. Prof. M. N. Bramlette of the Scripps Institution of Oceanography helped arrange for financial support in January 1953 so that I could devote nearly full time to this investigation. Prof. Howel Williams of the University of California, Berkeley, kindly contributed notes made on the September 20, 1952, flight to San Benedicto and has given me helpful advice.

A preliminary manuscript of this paper was read by Drs. Cordell Durrell, University of California at Los Angeles, and Gordon A. Macdonald, University of Hawaii. Drs. Helen Foster and Arnold Mason of the U. S. Geological Survey, Dr. A. G. MacGregor of H. M. Geological Survey, and Dr. M. Neumann van Padang of The Hague read the final manuscript. I am grateful to these people for their helpful comments and suggestions.

To my wife Joan I am deeply appreciative of her editorial advice and unstinted help.

Effect of the eruption on the fauna and flora

The indigenous fauna of Isla San Benedicto before the eruption in 1952 consisted of a single species of terrestrial song bird (the San Benedicto rock wren), sea birds, land crabs, and insects, the most noticeable of which were giant grasshoppers (HANNA, 1926, pp. 63-66). A number of migratory birds also visit the island (BRATTSTROM and HOWELL, 1956). Although the San Benedicto rock wren was seen in December, 1952, by Lewis WAYNE WALKER, it was not seen on any of the later trips and is presumed to be extinct (BRATTSTROM and HOWELL, 1956, p. 110). The remaining birds, crabs, and grasshoppers, which were nearly exterminated by the eruption, began to repopulate the island in 1953. Bats were seen at dusk in 1955, but it is not known whether or not they are indigenous. The marine invertebrate fauna is little known.

Prior to the eruption the most common land plants were grasses and a species of *Euphorbia* (HANNA, 1926, p. 63). The eruption killed nearly all of the plants of the island and of the ten previously recorded species only six were found still living in November, 1953 (MASON, 1953). *Euphorbia* was the most common post-eruption plant at that time. In March, 1957, fewer plants were found on San Benedicto than on the previous visit in May, 1955. Erosion of Bárcena ash and the pre-Bárcena surface by rain and wind has removed a large proportion of the plants which survived the 1952 eruption and were observed to be beginning to revegetate the island in 1953. If the present rate of plant destruction continues, San Benedicto may be a desert island without higher plants within a very few years.

The marine plants of San Benedicto have been described by DAWSON (1954), who collected algae from the newly formed Delta Lávico and elsewhere on the island in November, 1953.

Geological setting

Isla San Benedicto is located near the intersection of the east-west trending Clarió fracture zone (Menard, 1955, pp. 1167-1170) and the north-south trending submarine mountain range which extends from slightly north of San Benedicto nearly to Clipperton Island (Richards, 1956, 1957). Isla Clarión and possibly Isla Roca Partida (Fig. 1) appear to be related to the Clarión fracture zone, which extends over 2200 nautical miles west of San Benedicto and east to the mainland, and includes the trans-Mexico volcanic axis of Colima, Parícutin, Orizaba, and other volcanoes. Isla San Benedicto and Isla Socorro, 27 miles to the south, are located on the northern end of the range normal to the fracture zone and appear to be younger in age than the islands to the west. All of the Islas Revillagigedo are volcanoes which have built up from the ocean floor.

On San Benedicto volcanism appears to have progressed south along a narrow submarine ridge which extends over 20 miles north of the island. The island is composed of pyroclastic cones, eroded domes, and lava flows and tuff deposits which are not part of a recognizable structure. Volcán Bárcena erupted on the north flank of the eroded pyroclastic cone of Montículo Cinerítico (Pl. I). Cráter Herrera, northeast of Bárcena, probably is the remnant of the crater dome of a large pyroclastic volcano, the cone of which has been entirely eroded by waves.

The rocks of San Benedicto are alkali-calcic. Soda trachyte is the most abundant. Olivine trachybasalt is the least silicic lava collected on the island and soda rhyolite is the most silicic. The lava and essential pyroclastics erupted during the formation of Bárcena are composed of soda trachyte. Little differentiation of the Bárcena magma occurred during the eruption.

There is no historical record of any previous volcanic activity on San Benedicto. However, several historic eruptions are reported to have occurred on Isla Socorro (Richards, 1956), which may be the younger of the two islands.

Visit to San Benedicto in 1952 prior to the eruption

Fortunately Isla San Benedicto was visited a few months before the birth of Bárcena. In February and March, 1952, the Canadian yacht *Marijean* stopped briefly at San Benedicto for sport fishing and Bates (1952) took a photographic panorama of the southeast portion of the island from Punta Sur to northern Cráter Herrera (Pl. II, fiig. 1). These photographs show little change compared to a nearly identical panorama taken in 1925 by the California Academy of Sciences (Pl. II, fig. 2).

Photographs of San Benedicto taken in 1905 and 1925 by the California Academy of Sciences, in 1939 by Mr. Guy Silva, and in 1952 by Mr. Bates indicate it is unlikely that volcanic activity occurred during this period.

Birth of Bárcena and activity from August 1 to 5, 1952

Sources of information.

The birth of Bárcena was witnessed by the crew of the tuna clipper M/V *Challenger*. The following is an account compiled from a telephone interview with Captain Joseph da Luz (Dietz, 1953, pp. 24-25) and from personal interviews by the writer with Mr. Frank Rodriques, navigator, and Mr. Robert Petrie, fisherman. Statements by these men have been supplemented with a study of a magnificent series of eight photographs of the birth of the volcano taken by Petrie and three photographs taken by Rodriques.

Observations.

The *Challenger* arrived at Isla San Benedicto about 0530 (2) hours on August 1, 1952. Fishing commenced shortly after arrival in an area about two miles west of Punta Norte. About 0745 the eruption suddenly began as a white, thin,

(2) All times given in this paper refer to Pacific Standard time.

pencil-like column rose skyward behind Roca Challenger (3). According to DA LUZ rumblings were heard; PETRIE said the eruption began without sound. A few minutes later the steam column had largely dissipated and a dark gray-black or cement-colored column of ash and steam shot skyward (Pl. III). It did not appear incandescent. Almost immediately the eruption cloud began to spread laterally at the base. Impeded by Cráter Herrera to the north and Montículo Cinerítico to the south, the cloud was first seen from the *Challenger* as it spread west between Roca Challenger and Montículo Cinerítico. In the short time that the extension of the cloud pushed through the pass between the hills, another portion overtopped the junction of Cráter Herrera and Roca Challenger and reached Cerro López de Villalobos (Pl. IV). At this time a dense cauliflower plume had reached an altitude of about 4300 feet above sea level, based on an altitude of 500 feet for Roca Challenger in the foreground, and its horizontal extent was nearly 6700 feet. About 0805, twenty minutes after the beginning of the eruption, all of San Benedicto, with the exception of the Rocas Trinidad and the extreme north end, was obscured from view (Pl. V). This photograph shows that the base of the eruption cloud was rapidly expanding laterally. It had an approximate altitude of 1200 feet at Roca Challenger and about 2000 feet south of Montículo Cinerítico and at Cerro López de Villalobos. The vertical column appears to have ascended no higher than 4500 feet at this time, while the north-south extent was approximately 11,000 feet.

Several inches of powdery dust, ash, and cinders (up to about 12 mm in diameter) fell upon the deck of the *Challenger* as it headed away from the violently erupting volcano at full speed. The ocean, previously clear and blue, became turbid, due to suspended ejecta, and remained murky. Splashes in the sea southwest of Montículo Cinerítico indicated that bombs or blocks were ejected at the time the ship left San Benedicto. The *Challenger* reached Isla Socorro, 27

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(3) Named after the M/V *Challenger*.

nautical miles to the south, about noon. A column of dark ash from San Benedicto appeared to be rising very high into the sky and dust continued to fall on the ship. In the afternoon the *Challenger* left Socorro for Roca Partida, 60 miles to the west; on the way large pieces of pumice were seen floating on the water. The eruption plume was estimated to rise higher than 10,000 feet, as seen from Roca Partida, and dust still fell on the deck of the ship. At night on August 4 or 5, flashes of light from Bárcena were seen from Socorro, to which the ship had returned.

Da Luz notified the U. S. Navy Hydrographic Office of this eruption shortly after it began and a very brief statement appeared in the Hydrographic Bulletin of August 9 (U. S. Navy Hydrographic Office, 1952). Regrettably volcanologists appear to have been unaware of the activity until August 27, when R. S. Dietz read about it in the *Los Angeles Examiner*.

Discussion.

It is unlikely that the eruption began before the *Challenger* arrived at Isla San Benedicto. The initial photographs of the eruption taken by Petrie and Rodriques from the west side of the island show that the outline of San Benedicto was unchanged compared to a 1939 photograph of the same locality taken by Silva. The crew of the *Challenger* reported that the water in the vicinity of San Benedicto was clear before the eruption; there have been no observations of clear water around the island since the eruption.

A sketch map of San Benedicto before the eruption is shown in Figure 3. This map was prepared from photographs taken from the sea before the eruption and the map shown in Figure 2. The probable location of the vent, marked by an X on Plate I, was on the north flank of Montículo Cinerítico several hundred yards inland from shore. The thin, pencil-like white vapor column at the beginning of the activity may have represented the volatilization of ground water in the porous, ashy strata of Montículo Cinerítico — a

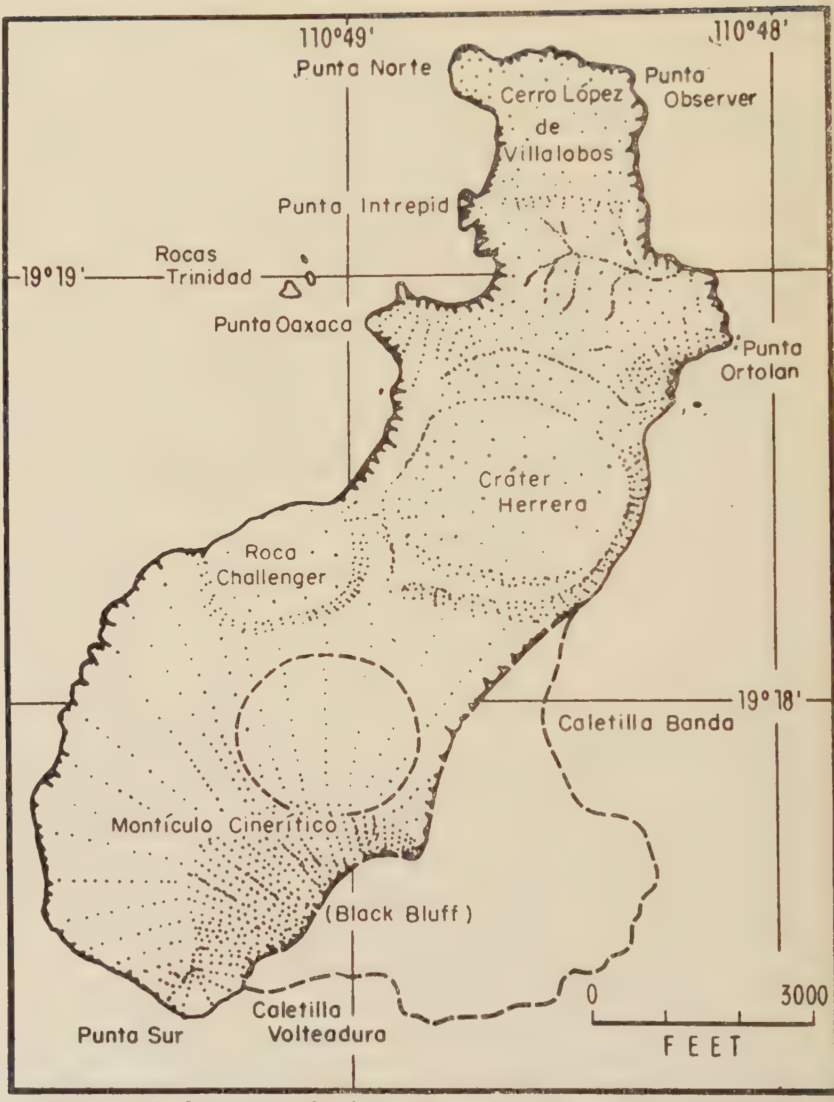

Fig. 3. - Outline map of Isla San Benedicto, before the eruption of Volcán Bárcena. Rim of Bárcena crater and new shoreline shown by the dashed line.

phreatomagmatic explosion (Stearns and Vaksvik, 1935, pp. 15-16). If the eruption had occurred offshore it is likely that more steam would have been generated.

The most striking feature of the birth of Bárcena was the behavior of the eruption column. Its horizontal spread increased much more rapidly than its vertical rise (Table 2) and resembled the base surge of an atomic explosion (U. S. Government Printing Office, 1950, pp. 41-44, 103-110).

Table 2.

Configuration of initial Bárcena eruption column

Illustration	Maximum altitude of eruption column in feet	Maximum lateral extent of eruption column in feet	Ratio of width to height
Pl. III	2300	1200	0.5
Pl. IV	4300	6700	1.5
Pl. V	about 4500	about 11,000	2.7

Formation of the cone and activity from August 12 to September 20, 1952

Sources of information.

On August 12 Isla San Benedicto was visited by the tuna clipper M/V *Intrepid* and its seaplane. Dietz later interviewed the pilot, Mr. Chester Blasko, and compiled a mimeographed report, part of which has been published (1953, p. 27). This report has been supplemented by the writer with a study of two 16 mm Kodachrome motion picture films that were taken from the air, and an interview with Mr. Ted Howell of the *Intrepid*. The visit by the *Intrepid* is the only source of information on the activity of Bárcena between August 5 and September 12.

Largely through the efforts of Dr. Gifford Ewing of the Scripps Institution of Oceanography, two B29 flights to Isla San Benedicto from Sacramento, California, were arranged with the Fifty-fifth Strategic Reconnaissance Squadron of the U. S. Air Force. The squadron was engaged in flying daily

weather flights over the Pacific Ocean so that by diverting the flights somewhat it was possible to accomplish both the weather mission and reconnoiter the activity of Bárcena. The flights took place on September 12 and 20. The scientific personnel present is listed in Table 1. An account of these two flights has been published by DIETZ (1953, p. 26) and WILLIAMS (1952). Their reports have been augmented by a study of air photography taken on the flights.

Observations.

In response to a radio report of the eruption from the *Challenger* the *Intrepid* proceeded to San Benedicto, arriving at 0300 on August 12. Bárcena was in continuous violent eruption, emitting a thunderous roar. No incandescence was seen; however, a dense pall of ash and steam greatly reduced visibility. In order to prevent contamination of the ship's bait tank by floating pumice, which discolored the water to a distance of fifteen miles around the island, the *Intrepid* continued on to Isla Socorro. Here the eruption column could be clearly seen and its altitude was measured by sextant angle to be greater than 10,000 feet. The eruption cloud was estimated to extend 150 nautical miles from San Benedicto and rain was falling from it.

BLASKO flew to San Benedicto from Socorro in the fish-spotting Piper Cub seaplane of the *Intrepid* between 1000 and 1100 on the 12th. The eruption was observed very close to the eastern or lee side of the volcano from an altitude of about 1800 feet. The roar of the eruption was clearly heard above the noise of the plane's motor. A cone of dust and ash was estimated by BLASKO to be about 1000 feet high and the crater about 1000 feet across. Very dense volutes of yellow-gray ash and steam, which directly above the crater appeared like a bundle of asparagus, appeared to rise indefinitely skyward from the crater. Occasional small eruption clouds or volcanic density flows spilled over the rim and rushed down the side of Bárcena (Pl. VI); they sometimes reached the sea. « Rocks as large as the galley » were ejected

which reached an estimated altitude of 2000 feet above sea level; they appeared to bury themselves upon landing on the cone.

The B29 on the flight of September 12 arrived at San Benedicto about 1300. The intensity of the activity was greatly reduced compared to that of August. During the hour at the island three yellowish-gray explosion clouds were seen at about 20-minute intervals. Each lasted 5 to 10 minutes and was composed of a stubby vertical column of ash and steam with a cauliflower texture (Pl. VII). The eruption clouds did not rise much higher than 2000 feet above sea level (4). A motion picture film taken on the flight shows that lava did not appear to be present in the bottom of the crater. A peculiar furrowing was present on the sides of the cone (Pl. VIII). The wind was from the southeast. No large blocks or bombs were ejected during the time that Bárcena was under observation and no large rocks were observed on the cone, which appeared to be entirely composed of pumiceous ash. The island was covered by a thick blanket of ash, which was ripplemarked on Roca Challenger.

On the B29 flight of September 20 the sky was comparatively free of clouds and a large number of excellent photographs were taken of the island. The cone was estimated by Williams to be 1500 feet high. No ash was discharged during the hour and one-half visit. Puffs of steam, and a little hydrogen sulfide, rose a few hundred feet above the crater rim at intervals of a few minutes and steam issued from many small vents around a dome of blocky lava at the bottom of the crater (Pl. IX). The vapour pressure of the steam was estimated to be only a few atmospheres.

Heavy rains had fallen on the island since the previous flight, establishing a drainage pattern, and ponded water was present in Cráter Herrera. Large pumice rafts were observed around the island, apparently formed from material eroded by rains or by wave erosion.

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(4) Erroneously reported to be 2800 feet above the crater rim in an earlier paper (Richards and Dietz, 1956, p. 158).

Discussion.

There is some question about the altitude of the cone during this period. DIETZ (1953, p. 27) compared photographs taken on the two September flights and stated that there had been no noticeable change in the form or size of the crater; no altitudes were given. WILLIAMS (1952) wrote that on September 12 (September 13 is given in his paper) the cone was 1000 feet high and almost a mile across at the base and on the 20th it was 1500 feet high. A study of the August 12 films and September photography by the writer indicates that there was little change in the altitude of the cone after August 12 and that it was about 1100 to 1200 feet high. The rapid growth of Bárcena is in agreement with the statement by WILLIAMS (1952) that almost surely most of the new cone was built during the first few weeks. The estimate by BLASKO that the crater rim was only 1000 feet in diameter in August appears to be low by a factor of two.

Air photographs taken in September show that a terrace, formed from tephra (5) fill and about 300 feet wide, was present in the southwest side of the crater (Pl. IX). Vulcanian explosions diminished in intensity in late August or early September with a resulting decrease in the size of the crater on the leeward side. In this area the gentle declivity reduced the tendency for internal landslides to keep the rim sharply edged and subsequent tephra deposition rounded the rim. The northeast rim was still so sharp in December that it was impossible to walk along it without straddling the rim.

DIETZ (1953, p. 27) described the appearance of steam, issuing from small vents around the dome, as a coronet (Pl. IX). The nature of the Bárcena coronet appears sufficiently similar to the phenomenon witnessed at Santorini to be called by the technical name « coronet », which was proposed by WASHINGTON (1926, p. 369).

The depth of the crater was determined photogramme-

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(5) A collective term for all fragmental volcanic material ejected through the air from a volcano (THORARINSSON, 1944, p. 210; 1956, p. 20).

trically from vertical air photographs taken on the September 20 flight. Photographs from two flight lines were examined using a stereocomparagraph (McNeil, 1952, pp. 603-622). Differences in spot altitudes were averaged in order to reduce errors resulting from tilt present in the photographs. Vertical control was based on sea level and an altitude of the crater rim obtained from a topographic map.

The crater floor had a computed altitude of about 420 feet above sea level. Assuming a maximum altitude of 1100 feet for the rim, the crater was nearly 700 feet deep. On the September 20 flight Dietz (Richards and Dietz, 1956, p. 160) visually estimated that the crater was 700 feet deep. The dome on the crater floor was about 25 feet high and 180 feet in diameter. Maximum width of the crater rim, determined later by photogrammetry, was about 2300 feet.

Solidified lava in the vent indicated the end of the first period of activity of Bárcena. Because no reports from fishermen were received until early November, the volcano appears to have entered a period of repose which lasted until enough pressure was generated to extrude additional lava into the crater.

Crater activity from November 12, 1952, to February 27, 1953

Sources of information.

Radio reports from fishermen of renewed activity at Bárcena were received at the Scripps Institution of Oceanography in November, January, and February (see Table 1). Additional reports were obtained by radio and interview during the time the writer visited San Benedicto on the yacht *Observer* in mid-December. On November 15 the writer made his first visit to San Benedicto on an observation and photographic flight, which was made in a PBM amphibian by Utility Squadron Seven from the North Island Naval Air Station in San Diego. Interviews in 1953 were made with Captain Paul Lynn and Mr. Jack Baker of the M/V *Cape Beverly*, and

with Captain Edward Mitchell of the M/V *Columbus*. Baker and Mr. Robert Morton, of the Columbus, took photographs of the activity.

Observations.

Captain Neves of the M/V *Constitution* radioed the first report of renewed activity at Bárcena on November 12. His message stated: « Intermittent puffs of white smoke frequent at times with flame shooting above the crater. The light of flame reflecting on low clouds visible 40 miles at night ». A second radiogram reported that « smoke », which was thicker on the 13th, was seen from the south side of Isla Socorro, a distance of about 36 nautical miles. Apparently the *Constitution* returned to San Benedicto because on the 15th a message was received that when the ship was abeam of the volcano a « low rumbling » sound was heard as each puff of steam appeared above the rim of the crater.

On the PBM flight of the 15th the crater was observed to be more than half-filled with viscous lava in the shape of a dome (Pl. X). The surface of the lava did not appear incandescent. A few small, sporadic explosions of steam and a little ash occurred from the crater while the plane was flying around the island. No explosions were noted during the short time that the interior of the crater was under surveillance. A continuous weak emission of steam occurred from near the center of the dome.

On the 19th Captain Zeluff of the M/V *Paramount* reported that a radio message from the M/V *American Ladies* to him stated that three « medium-sized » eruptions spaced one-half hour apart occurred during the night of the 16th. On the 17th activity consisted of steady « smoke and steam », with minor eruptions every five minutes that produced a steam and ash column which rose to 1000 feet (presumably above the crater) and obscured most of the island.

The *Paramount* approached San Benedicto on the 19th and radioed the following message:

« Volcano first observation 25 miles. Minor eruption fre-

quency 2 ½ minutes. Duration frequency largest eruptions averaged 40 to 45 seconds. Smaller eruptions averaged 12 to 17 seconds. Plane followed large to smaller eruptions. Only largest contained smoke or discoloration. Between eruptions starting and stopping are abrupt. Between smaller they are diffused. Would consider actions minor at present ».

Zeluff later told the writer that the eruptive activity occurred about every 45 minutes and at night incandescent boulders were hurled 100 to 200 feet above the crater rim. They appeared to fall back into the crater.

No further reports were obtained in November. On December 4 Captain Perreira of the M/V *Star of the Sea* witnessed essentially the same type of activity as described by Zeluff on November 19. However, eruptions of dark-colored steam and ash, which rose 100 to 200 feet above the crater, occurred about every 20 minutes. Perreira did not see any dark-colored eruptions on a visit to San Benedicto on December 8.

At 1930 on the night of the 8th, Captain Carmelo Marino of the M/V *Santa Margarita* reported that « fire came out of the crater » and five blasts occurred between 2300 and 0030 on the 9th. The observations were made from about ten miles west of San Benedicto. (The « fire » was probably reflection of light from incandescent crater lava on low clouds or steam from the crater and presumably the blasts were due to explosions in the dome).

During the afternoon of December 9 two kinds of crater eruptions were noted by the writer as the yacht *Observer* approached Isla San Benedicto from the northwest. The first consisted of white clouds of steam erupted every few minutes which lazily rose only a few hundred feet above the crater rim before dissipating. The second consisted of small, darker, poorly-defined cauliflower eruptions of steam with a little ash, which erupted on an average of every 40 to 50 minutes. They commonly ascended about 3000 feet above sea level before the top of the column was flattened by the prevailing northerly wind. A rumble of about five seconds duration preceded some

eruptions of steam and ash from the crater during the evening of the 9th (Lewis W. WALKER, personal communication).

The crater was entered by WALKER and the writer on December 10. The lava dome had altered since November 15; instead of a single structure it was composed of two parts consisting of an outer doughnut-shaped dome of brownish-black, older lava and, in the center of the outer doughnut, an elliptical dome of fresh-appearing black lava. An annular depression or « moat » separated the inner and outer part of the dome (Pl. XII). The older lava was surfaced with fragmented lava rubble; the younger had no noticeable rubble. Breadcrust bombs and lava ejecta littered the ash cone and older lava. Steam eruptions, which started and stopped slowly, occurred from the western side of the moat. Darker eruptions of steam and a little ash originated from a crater vent in the middle of the black lava. They started and stopped abruptly. Weak orange incandescence periodically was visible in localized areas in the center. The west margin of the outer dome was estimated to be 50 feet high. It was coated with yellow solfataric deposits. A roar like that of a jet airplane from escaping steam emanated from a solfatara amid a jumbled cluster of lava boulders south of the inner dome. The noise in the crater sometimes was loud enough to require shouting to a person standing nearly. South of the outer dome, solfataric activity had excavated two craterlets on the floor of the main crater between the outer dome and the side of the cone with estimated depths of over 30 feet and rims about 100 feet in diameter. Their size, and the length of time that sufficient gas pressure existed to keep the craterlets excavated suggests that they were of primary magmatic origin.

On the lee or south side of the rim there were fresh deposits of soft, flour-like ash (Pl. XI). Edward NAPONELLI, seaman from the *Observer*, and the writer walked along the south rim to the graben area above the Delta Lávico. In places the unconsolidated ash was so soft that one would sink into it above the knees. While on the south or leeward rim, an eruption of steam occurred in the crater and quickly envel-

oped us. A little gritty ash was present in the steam and there was an almost overwhelming odor of burning sulfur (sulfur dioxide ?). Flecks of yellow sulfur were abundant on the inner rim and leeward wall of the crater indicating that sulfur was condensed directly from the steam eruptions.

Intermittent eruptions of ash and steam continued until the morning of December 12, when a dark cloud (described later) descended the cone at dawn. Bárcena burst into a continuous discharge of steam and a little ash after the ejection of the cloud. The eruption column rose to about 3000 feet above sea level before it was flattened by the prevailing wind (Pl. XIV).

The western crater rim has a greater elevation than the eastern rim. On december 12 this slope was measured and found to be 7 degrees. The exterior slope of Bárcena was measured and determined to be 33 degrees.

The last reports of activity in December were received from Captain Zolezzi of the M/V *St. Mary* and the Master of the M/V *Shasta* who radioed the writer (returning to San Diego on the *Star of the Sea*) that on the 13th eruptions of steam and a little ash occurred every 20 minutes until noon, when the eruptions became continuous and darker-colored compared to the color of those of the 12th.

Isla San Benedicto was visited on January 4, 5, and 12, 1953, by the M/V *Cape Beverly*. Captain Lynn later told the writer that on both visits Bárcena continuously emitted light gray steam and ash which rose to slightly over 3000 feet above sea level and extended nearly to Socorro. In the lee of San Benedicto volcanic dust fell on the ship. (It may have resulted from deflation rather than volcanic activity at that time). At Socorro there was a distinct odor of sulfur, not as pungent as hydrogen sulfide. The intensity of the odor increased when the *Cape Beverly* steamed from Socorro to San Benedicto.

Photographs taken by R. H. Morton of the M/V *Columbus* show that only intermittent puffs of light-colored steam were being erupted from the crater of Bárcena on February

27. Because no steam and ash was erupted on the March visits to San Benedicto it is probable that eruptive activity stopped by the end of February. There have been no verified reports of any activity other than solfataric steaming after the end of February, 1953.

Development of the Delta Lávico: December 8, 1952, to March 1, 1953

During this period data were obtained by radio and interview from tuna fishermen and from a visit to San Benedicto by Lewis Wayne Walker and the writer between December 9 and 12.

Initial development.

At 1345 on December 8, a landslide originated on the southeastern sea cliff of Volcán Bárcena half way between sea level and the top of the 160-foot cliff. It was witnessed from the M/V *Star of the Sea,* which had just arrived in the area. According to Captain Manuel A. Silva, additional landslides occurred during the afternoon and by 1430 a cave-like depression had formed. About 2030 (Co-captain Perriera believed that the time was 2105) an « enormous amount of black smoke » was either emitted from the side area or from the crater and lava began to flow from the depression in the side of the cliff. The observations were made from one or two miles east of the new vent. That night crater activity consisted of lava incandescence and audible detonations.

On the morning of the 9th brownish-colored eruptions and an occasional rumble came from Bárcena. Lava from the vent flowed down the cliff, across the beach, and reached the sea at 0830. The flow became more active at noon. Captains Zeluff and da Luz reported this activity (Table 1).

The yacht *Observer,* with the writer aboard, rounded Punta Observer (6) (Fig. 2) at 1617 on the 9th, and by 1710 Captain Charles G. Zamora had anchored the yacht abeam of the vent of the new flow in twenty fathoms of water 2700

(6) Named after the ship.

feet from shore. Measurements were made of the size of the beginning lava flow by RCA CR-103 radar (Zamora), using the one mile range, and sextant angles (Richards). A tabulation of measurements on the 9th, and the next two days, is given in Table 3. The deltaic shape of the flow prompted the name Delta Lávico (lava delta) for this feature.

At 1705 without warning white vapor began to escape from the sea cliff about 2200 feet north of the delta and it soon became apparent that a fumarole had formed at, or slightly below, sea level; no lava issued from this new vent. During the night and early morning odorless vapor from the fumarole rose as high as 300 feet and at times was dense enough to obscure the Delta Lávico; the vapor was much more abundant than steam generated at the margin of the flow by the glowing lava in contact with sea water. By the morning of the 10th a large concavity had formed in the 30-foot-high cliff and the beach was destroyed. Visible activity stopped by the morning of the 12th (7).

Above the Delta Lávico the crater rim had faulted and a small graben about 1000 feet long with a 12 to 15 foot vertical displacement had formed, probably at the time lava broke through the base of the cone. Minor vertical fractures developed *en échelon* between the lateral edges of the graben and the vent 700 feet below the rim.

The Delta Lávico was an impressive sight seen from the *Observer* before dawn on the 10th. The mouth of the vent was a bright orange color with an occasional flare of orange-white. An estimated maximum temperature of about 1200° C, based on a color scale of temperature (yellowish red to incipient white heat), was indicated which probably resulted from burning gas. Color below the mouth of the vent graded from red-orange to dull red. The top surface of the flow had cooled and was black. At the active margin of the flow the color ranged from dull to bright red, the latter color appearing when large blocks toppled off the top of the forward

(7) In May, 1955 a very small amount of vapor was issuing from a warm spot at the base of the sea cliff in this locality.

Table 3.

Growth of the Delta Lávico: December, 1952, to March, 1953

Date	Time	Maximum altitude of vent in feet	Maximum altitude of delta below vent in feet	Width in feet	Seaward extent in feet
December, 1952					
9	0730	about 80	—	—	—
9	1700	140	45	700	700
10	0645	—	65	—	900
11	0600	190	75	1170	900
March, 1953					
9	—	260	125	see below	
April, 1953					
16	—	> 208 < 260	about 120	4240	2160

margin of the flow exposing the incandescent interior. As the lava advanced seaward a rumbling roar was produced by grinding of boulders. An especially loud rumble was usually followed by a tremendous hiss, as incandescent rock suddenly became quenched by the sea. The small amount of steam generated from these quenchings rose 30 to 75 feet above sea level in sporadic bursts (Pl. XV). Immediately seaward of the flow margin the water was little heated and it was possible to maneuver a skiff directly next to the flow and pick up samples of lava which only a few minutes before had been glowing.

Fumes from the vent were darker than the white steam from the margin of the flow (Pl. XV). No odor was perceptible on the 10th and 11th aboard the *Observer* east of the delta because a north wind was blowing. Leeward of the flow there was a faint smell of sulfur.

On the morning of the 11th the *Observer* left San Benedicto for the Islas Galápagos, and WALKER and the writer were transferred to the M/V *Southern Queen*. A flight over and around Bárcena in the ship's fishspotting Piper Cub seaplane, piloted by Victor SILVA, was made possible by Captain John RIPPO, Jr. The concentric growth of the Delta Lávico, relation of the flow to the beach, and beginning development of lava tongues could be clearly seen from the air (Pl. XVI). A diagrammatic sketch of the flow at 0600 on this date is shown in Fig. 4.

An upset landing by skiff was made on the beach of Caletilla Volteadura (Turnover Bight) after the flight. A planned ascent of the volcano and a night camp in the crater was given up because of the loss of two cameras (RICHARDS and WALKER, 1954).

The west side of the Delta Lávico could be approached from the beach (Pl. XVII) and one could stand within a few feet of the advancing flow without too much discomfort, even though incandescence of the flow interior was clearly visible between blocks. The viscous trachyte lava advanced by boulder-sized blocks rolling from the top or front of the

flow to the base. Lava boulders fell virtually at our feet on the pumice beach; they did not break apart. Several boulders,

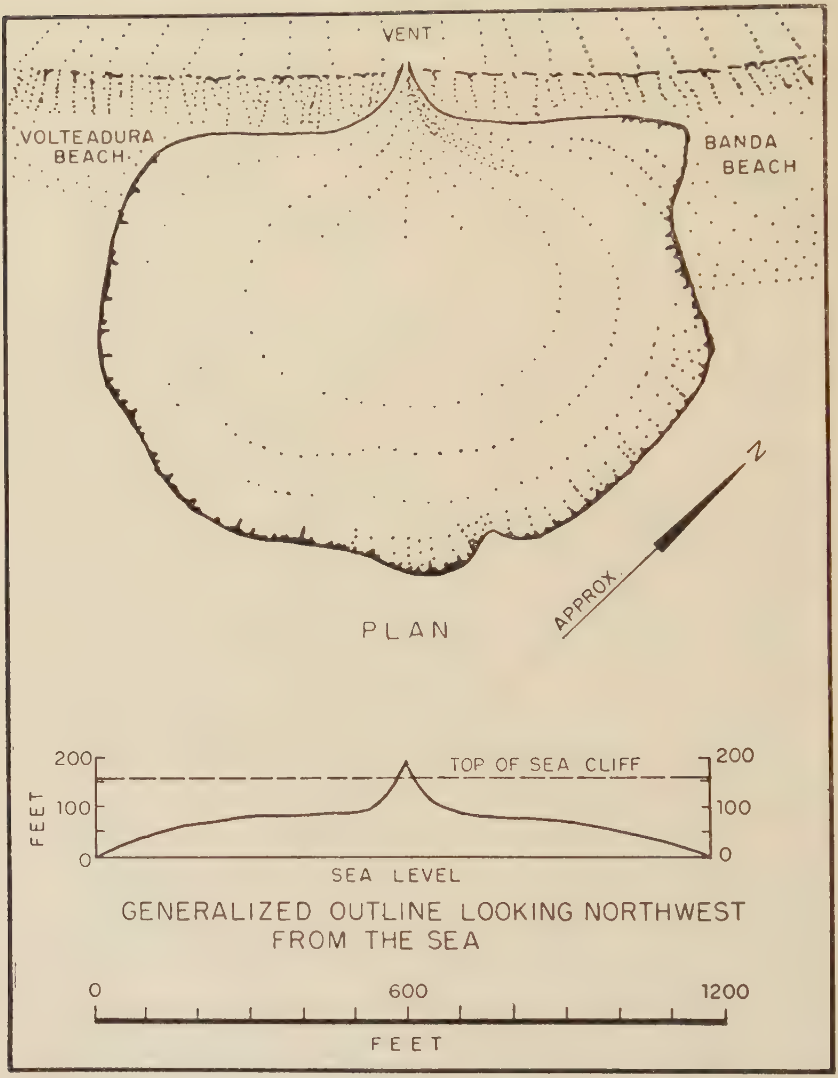


Fig. 4. - Sketch of the Delta Lávico at 0600 on December 11, 1952.

three to six feet in diameter, fell into the sea near shore and two successive waves washed over them before the glow was

extinguished. Occasionally it took up to one-half minute for the sea to subdue visible incandescence. During this time the boulders would steam quietly and no physical change due to fracturing or exfoliation was observed. The slope of the flow margin on land was estimated to be about 60°, appreciably steeper than the 14° seaward margin opposite the vent.

At 1800 on December 11 measured marks were made on the cliff face west of the flow margin by Walker. By 0600 on the 12th the lava had advanced to the mark placed 40 feet from the margin 12 hours earlier.

Later growth.

The Delta Lávico was reported active on January 4-5, and 12, 1953, by Captain Lynn of the M/V *Cape Beverly*. A photograph taken by Jack Baker on one of these visits shows that the flow had nearly reached its maximum size. Lava movement was predominantly on the north, northeast, and south sides. Photographs taken by R. H. Morton of the M/V *Columbus* on February 27 show that the flow was only slightly active on the south side.

The R/V *Paolina T* of the Scripps Institution of Oceanography arrived at San Benedicto on March 9. There was no activity other than solfataric steaming and the flow had grown appreciably compared to December. The seaward slope had increased from 14° in December to about 40° in March. An average altitude of the flow and the height of the top of the vent was determined by means of a surveying altimeter (Table 3). The width and seaward extent of the flow in March was the same as in April. Although in early March the flow was too hot to walk on except at the outer edges, the mouth of the vent was entered in the latter part of the month by a group of tuna fishermen from the M/V *Southern Queen*, some of whom put water into their boots to keep their feet cool. The flow could be traversed in November, 1953, without discomfort. A vertical air photograph of San Benedicto taken on April 16 shows the Delta Lávico before erosion began (Pl. XVIII). The dark areas on the delta

undoubtably represent the last flows of lava in January and February.

Solfataric phase : March 1953 - ?

Observations of Isla San Benedicto were made on two Scripps Institution expeditions and six U. S. Navy photographic and observation flights between March, 1953, and November, 1954 (Table 1).

On the March, 1953, visit to Bárcena solfataric activity was of two types and occurred in four different locations. The first, and most impressive, type was a weak continuation of the December activity in the craterlets south of the outer dome in Bárcena crater. Gas pressure was still sufficiently strong to keep the southeast solfatara craterlet V-shaped and clear of debris. The south craterlet had been partly filled by slumping of the crater wall. The second type of activity was a quiet emission of steam from the cooling lava in the crater, on the Delta Lávico, and in the depression area in the side of the cone above the mouth of the Delta Lávico vent.

A stereoscopic examination of vertical air photographs taken on September 21, 1953, shows that the southeast solfatara still contained a steep, V-shaped depression, indicating that it continued to be active. This solfatara is located southeast of the crater above the Delta Lávico magma conduit (Pl. XVIII).

On the November, 1953, visit the secondary solfataras in the crater emitted superheated steam (Zeller, 1953).

Vertical air photographs taken on August 6, 1954, show that the southeast solfatara was partly filled with sediment from Bárcena crater wall. Hence primary solfataric activity stopped between September, 1953, and August, 1954, and Bárcena can be considered dead as of this period. It is unlikely that the volcano will become active in the future because of the brevity of tuff-cone or tephra eruptions (Bishop, 1901).

The appearance of Isla San Benedicto today is virtually

the same as shown in a photograph taken in March, 1955 (Pl. XIX).

Solfatara deposits

Samples from solfataras in Bárcena crater and above the Delta Lávico vent were collected in March and November, 1953, and studied using an X-ray diffractometer. Sulfur and halite were recognized and compared to known standards. The samples may have contained gypsum, but ammonium chloride was not found. The predominant mineral was sulfur. Solfataras often had surficial layers of encrusted sulfur over one-half inch thick. Sodium chloride may have precipitated from sea salts in the air, although the mineral halite is also known as a sublimation product (von Wolff, 1914, p. 585).

Tephra avalanches

General statement.

Volcanic eruption clouds that descend under the influence of gravity because of a greater density than air are commonly called *nuées ardentes, Glutwolken,* or glowing avalanches (clouds). They are a type of density flow. In the weaker types incandescence is not necessary but the cloud must be hot. A number of classifications of glowing avalanches have been proposed; references are listed in a recent paper by Williams (1957, pp. 59-60).

Incandescence of volcanic density flows was never witnessed at Bárcena, perhaps because all observations at close range were made during the day when the glow of liquid magma particles would tend to be obscured by sunlight, hence the term glowing avalanche appears somewhat inappropriate. In order to avoid the connotation of incandescence, when it is uncertain whether or not it existed or when it is known that it did not exist, a more general term, tephra avalanche, is proposed. Tephra avalanches can include all apparently incandescent *nuées ardentes* as well as the range

of weaker *nuée ardente* phenomena including ash and/or block flows (PERRET, 1937, p. 45, 65).

Avalanche of August 12.

A tephra avalanche that bulged over the crater rim and rushed down the flank of Bárcena is shown in Plate VI. The following characteristics were determined from Kodachrome motion pictures: the avalanche did not appear to be incandescent, next to the cone it appeared to have a rolling rather than a sliding motion, it descended from the lowest point on the crater rim, and there appeared to be a gaseous dilation from the center of the avalanche. Insufficient detail exists in the films to tell whether or not the avalanche furrowed the cone. During the time it was ejected from the crater a dark ash and gas column, which had the appearance of a closely packed bundle of asparagus, rose skyward from the crater in normal vulcanian fashion.

Avalanche of December 12.

On the morning of December 12 a small tephra avalanche or ash flow was witnessed at close range by WALKER and the writer from the beach west of the Delta Lávico. During the previous three days Bárcena had been erupting intermittent, poorly defined volutes of gas and a little ash from the crater. At 0512 in the pre-sunrise twilight, suddenly, and without warning, a large black-appearing cloud poured over the graben area of the crater rim, rushed down the cone, crossed the Delta Lávico, and spread out to sea. Within about one minute — actually it seemed to appear almost simultaneously — the edge of the cloud passed overhead and at 0513 a shower of dust and ash fell upon us. The particles ranged in diameter from about 0.1 to 3 mm and averaged about 0.5 mm. At 0520, eight minutes after the cloud appeared, rain fell as we retreated to the west end of Volteadura Beach. Dust, ash, and water mixed to form a light rain of large muddy drops, somewhat like a hail-storm. The rain stopped at 0540. According to Captain PERREIRA, who was

readying the *Star of the Sea* about three miles offshore preparatory to picking us up, within minutes after the beginning of the eruption the entire island, with the exception of the extreme north and south ends, was obliterated from view. However, from Volteadura Beach the Delta Lávico could be seen at all times, indicating that the dust pall was not dense. Our location at the beginning of the eruption was about 1000 yards from the graben area of the crater rim. Hence the speed of the avalanche was about 30 knots or more. It appeared to descend the slope and travel out to sea very rapidly. The wind direction, observed from the beach, was westerly or blowing in the same direction that the cloud traveled. Bárcena became continuously active after expulsion of the avalanche, belching a light-colored cloud of gas and a little ash (which appears dark in Plate XIV).

Discussion of avalanches.

The Bárcena tephra avalanches observed in August were initiated from an open crater in which it is very unlikely that lava was present. This general type of eruption, of which the Soufrière in St. Vincent is the type example, has been called *nuées ardentes d'explosions vulcaniennes* by Lacroix (1930, p. 461) and vertically initiated crateral *nuées ardentes* by MacGregor (1952, Table II; 1955, p. 4). *Nuées ardentes d'explosions vulcaniennes* are accompanied by vertically rising cauliflower clouds of ash (van Bemmelen, 1949, p. 193). Bárcena tephra avalanches of August appear to have the two essential characteristics of *nuées ardentes* according to Perret (1937, p. 48): « an extremely rapid transport of crater material in a horizontal direction to considerable distances, and a lava in itself highly explosive and continuing to discharge gas throughout its mass as long as its temperature remains sufficiently high ».

The formation of tephra avalanches at Bárcena is not surprising considering the explosiveness of the volcano. A formula for calculating the explosiveness of a volcano has been devised by Rittmann (1936, p. 162), in which the index

of explosiveness is equal to the amount of loose material (ejecta) divided by the total amount of material erupted. The index for Bárcena is about 90 per cent. It is unusually high for a Pacific Ocean volcano, where the average index is only 3 per cent (Rittmann, 1936, p. 167). Parícutin, which did not produce tephra avalanches, has an index of about 65 per cent.

The composition of the tephra contained in the avalanches presumably was the same as the soda trachyte tephra of the cone.

The tephra avalanche of December can be regarded as a decadent, vertically initiated avalanche ejected from the summit crater of a dome. Only a single avalanche is known to have been expelled and it occurred so rapidly and unexpectedly in the dawn twilight that little can be said in addition to the above narration of the experience. The avalanche definitely did not appear to be a landslide of unstable hot ash from the flank of the cone or an *avalanche produite par décollement* (Lacroix, 1906, p. 657) or hot avalanche (Perret, 1924, pp. 89-92). It presumably originated without explosion because of the absence of warning sound.

Discussion of furrows.

Furrows which formed on the flank of Bárcena prior to September 12, 1952, have been studied by inspection of air photographs taken on the 12th and 20th. A summary of data on the furrows obtained from these photographs is compiled in Table 4.

A satisfactory hypothesis of furrow formation must account for the following features. Above the change in slope of the cone (Pl. VIII; Pl. XX; Pl. XXI): (1) appearance of the beginning furrow below the crater rim, (2) U-shape, (3) straightness, (4) parallel, non-coalescing arrangement; below the change of slope (Pl. VIII; Pl. XX; Pl. XXII): (5) increasing width down slope, (6) turbulent patterns on the cone, and (7) local deposition at the lower ends of some furrows, between Bárcena and Cráter Herrera (Pl. VIII). The following are conceivable methods of furrow formation:

Table 4.

Summary of data on Bárcena furrows

Distribution	Areal	Best developed below low areas of crater rim on east and west flank of cone. Less well developed below high areas of rim at junctions between Bárcena, Montículo Cinerítico, and Roca Challenger.		
	Vertical	From about 40-70 feet below rim to change of slope on cone, which occurs, on an average, about 500 feet above sea level. At southeast side, where there is practically no change of declivity, the furrows extend to sea cliffs.		
		Above change of slope	At and below change of slope	
Size estimate	Width	About 10-20 feet	Wider	
	Depth	About 3-10 feet	Apparently not as deep	
	Length (8)	Depends on change of slope position and location of furrow relative to higher areas of crater rim. Average length about 800-900 feet, maximum length about 1400 feet.	Variable. Where recognizable as a furrow usually only a few hundred feet long. Where change of slope is great the furrows appear to terminate abruptly (Pl. XXIII).	
Shape	Cross section	U-shaped with a tendency for crests to be wider than troughs.	Slope change gradual (Pl. XXII).	Slope change relatively abrupt (Pl. XXIV).
			Irregular, shallow, and U-shaped	See below

(8) Based on a 33° external slope of the cone and a crater altitude of 1100 feet.

Table 4 (continued)

		Above change of slope	At and below change of slope	
			Slope change gradual	Slope change relatively abrupt
Shape	Normal to length			Ridge and valley topography
	Parallel to length of furrow		Gentle asymmetrical ridge crest up slope	Steep asymmetrical ridges with ridge crest up slope
	Plan	Straight and parallel	Poorly developed herringbone pattern	Poorly developed ridge and valley topography
Characteristics	1. Length normal to crater rim. 2. Individual furrows do not coalesce. 3. Upper end of furrow develops gradually from unfurrowed area immediately below crater rim. However, it is possible that tephra fallout, when eruption clouds cross the rim, has partly or completely buried the upper ends of furrows. 4. Width of best-defined furrows show little variability, others diverge slightly down slope. 5. Boulders may be present near the upper end of furrows.		1. Where change of slope is gradual the furrow is recognizable below change of slope. 2. Where change of slope is abrupt furrow terminates. 3. Furrows tend to coalesce. 4. Lower ends of furrows diverge down slope. 5. Turbulence patterns in ash are more intense where declivity is the greatest. 6. Furrow debris may occur at lower ends when the change in declivity is moderate.	

(1) rain erosion, (2) avalanches of bombs or blocks, (3) ash landslides from the crater rim, and (4) tephra avalanches.

Rain erosion as a method of formation can be immediately discarded because of the size of the features and absence of dentritic drainage. (However, rain erosion later modified the furrows and superposed a dendritic drainage upon them).

Furrow erosion by bombs has been observed at Parícutin Volcano. Here the orientation of the initial furrows was dependent upon the direction of travel of the descending bombs; they were often curved rather than straight (Howel WILLIAMS, personal communication). Shortly after landing the bombs tended to roll in the same channels, about two feet wide and deep, straight down the volcano (Ray WILCOX, personal communication). The beginning straightness and size of the Bárcena furrows appears to preclude this mode of formation. In addition, no accumulation of bombs or blocks has been found at the base of Bárcena; bombs were abundant at the base of Parícutin.

Bárcena furrows originate both below the sharp edge of the windward (eastern) rim and the rounded top of the leeward (western) rim. If ash landsliding took place very near the rim on the leeward side, how could newly deposited ash build up a regular appearing rim and yet not completely fill the furrows below? Similar problems would be confronted if landslides were postulated for the windward side. Landslides also presumably would occur on both sides of the rim. The scars on the interior of the crater do not show furrowing of the type exhibited on the exterior of the cone (Pl. IX).

Fewest obstacles are encountered on the assumption that tephra avalanches created the furrows. BELL (1942) has observed that turbid underflows in lakes, dust storms, *nuées ardentes,* and other dust clouds of volcanic origin exhibit much the same behavior; however, little is known about the mechanism of erosion by tephra avalanches on the comparatively steep slopes of volcanoes. Tephra avalanches usually deposit material rather than erode, but on occasion they have

furrowed Montagne Pelée (LACROIX, 1904, p. 217; PERRET, 1937, p. 33). The boulders present at the upper end of some of the furrows (Pl. XXI) may have been ejected from the crater independently from the emission of tephra avalanches, or perhaps they were deposited as the tephra avalanches dilated when flowing over the crater rim. Furrows on the eastern side of Bárcena extend slightly more than half-way to the base of the cone (Pl. VIII). Presumably the tephra avalanches lost their ability to erode in this region, and it is likely that the dark areas at the base of the furrows represent deposition of furrow debris.

Summary of envisioned activity.

At the birth of Bárcena on August 1, 1952, two phenomena occurred simultaneously. One component of the eruption ascended vertically as *nuées volcaniennes* (LACROIX 1930, p. 44) and the other flowed in a horizontal direction. The motivating force of lateral flow probably was a combination of base surge, auto-explosion of the incandescent ash or lava particles contained in the cloud, and horizontal trajection.

The cone grew rapidly by tephra fallout from the eruptions and deposition from the tephra avalanches. Sometime between mid-August and September 12, toward the end of the violent phase of cone formation, tephra avalanches became intermittent. Strong, vertical, vulcanian-type eruptions continued during this period. By September the tephra avalanches contained less auto-explosive material and hence were less active. Instead of rolling they probably slid and eroded, causing the formation of furrows. The avalanches tended to descend from the lowest areas of the crater rim and furrowing was most intense below these areas. Slight slope changes caused pronounced differences in the behavior of the avalanches. The greater the declivity the greater became the turbulence of the density flow, with attendant erosion and deposition.

Only one additional tephra avalanche is known to have occurred after domal extrusion of lava into the crater. It

occurred in mid-December after a period of comparative repose and three days after lava had broken through the base of the cone. This avalanche may have been caused by a sudden increase of gas evolution together with a clearing of a partly obstructed conduit. At the beginning of the eruption the initial part of the hot gaseous cloud, which contained dust, ash, and perhaps conduit debris, filled the crater and overflowed the rim at the graben above the Delta Lávico. Later, gas effervescing from the magma was insufficiently heavy to descend as tephra avalanches and consequently rose in normal vulcanian-type eruption.

Development of the crater domes

General description.

In mid-September a proto-dome had formed about 25 feet high, 180 feet in diameter, with an estimated volume of 21,000 cubic feet above the floor of the crater (Pl. IX). The blocky exterior of this dome probably indicates the effusion of viscous lava rather than an upheaved conduit plug.

Active extrusion of lava into the crater occurred on, or perhaps before, November 12. Lava more than half-filled the 700-foot-deep crater by the 15th and formed a dome, which was approximately 1200 feet in diameter and had an estimated volume of 200 million cubic feet above the crater floor of mid-September. The following features of the dome were observed by stereoscopic examination of the November 15 oblique air photographs (Pl. X): (1) the top of the dome was convex, (2) its sides were steep, (3) no talus was visible on the north, east, and west sides — the south side was not photographed, (4) its top surface had more than one raised concentric ridge, (5) a summit depression was present, (6) two tumuli were located west and south of the depression, (7) at the base of the dome there were localized fumarole deposits, and (8) steam eruptions appeared to originate from the summit depression.

Additional lava was extruded into the crater between

November 15 and December 10 forming a second dome in the center of the first, which was slightly enlarged. This

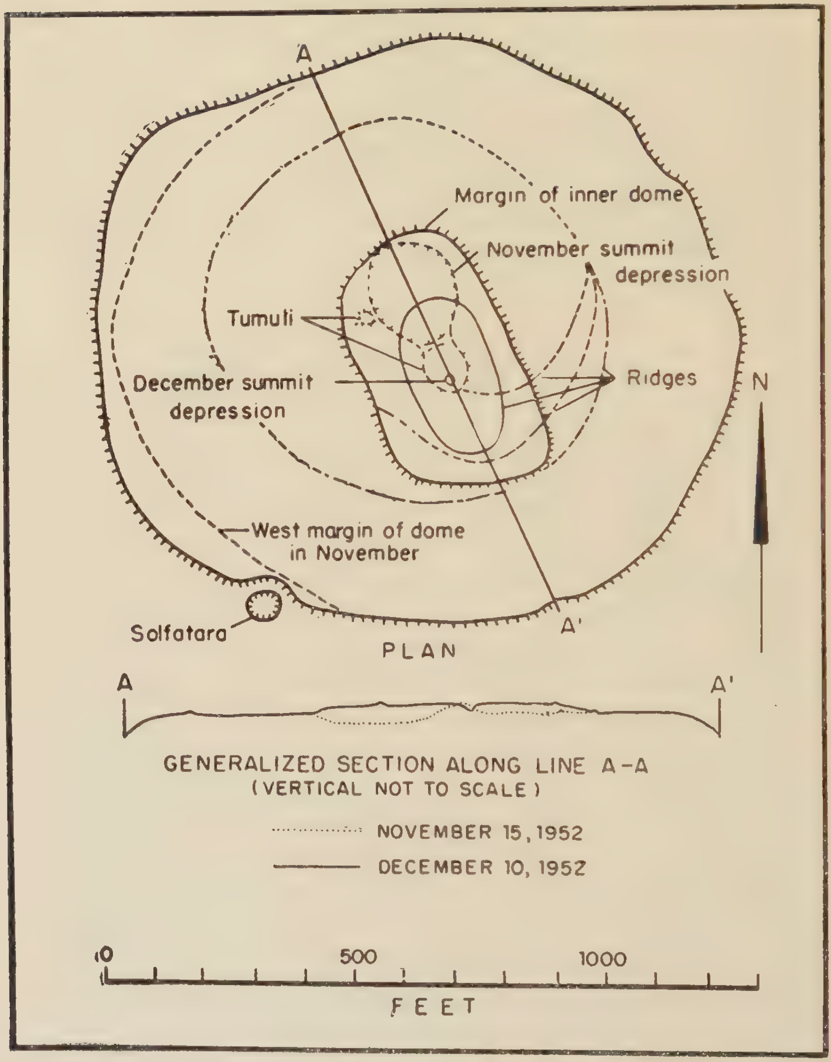


Fig. 5. - Sketch of Bárcena crater domes on November 15 and December 10, 1952.

second or inner dome had an elliptical shape with a 570 foot northwest major axis and a 300 foot northeast minor axis.

Its height was about 10 to 20 feet above the outer dome. An estimation of volume is difficult; 2 million cubic feet was calculated using the formula of an elipse for determining the area and 15 feet for the altitude. The fresh appearance of the inner dome on December 10 (Pl. XII) indicated that it was probably extruded in early December rather than in November. It likewise had a summit depression and, except for the absence of tumuli and only one raised ridge, was similar to the outer dome of November 15.

A diagrammatic plan and cross-section of the writer's interpretation of the appearance of the domes on November 15 and December 10 is shown in Figure 5.

The cone-shaped depression of the inner dome was first examined in the field in November, 1953. It was over 30 feet deep and there was a higher proportion of block lava (Finch and Anderson, 1930, p. 249; Finch, 1933) in it than anywhere else on the volcano.

Envisioned activity of dome development.

The following sequence of activity of dome development at Bárcena is envisioned by the writer: When the cone-building phase stopped in the middle of September an endogenous small dome was extruded from the conduit orifice before solidification of the upper conduit magma. The lack of reports from the tuna fleet before November 12 probably indicates that the active phase of extrusion did not occur until about the 12th. Bárcena crater was half-filled with a dome of viscous trachyte by the 15th. However, by this date the side of the dome had cooled (indicated by the presence of fumarole deposits) and it is possible that the dome formed before the 15th. It undoubtably grew rapidly. A vertical growth of about 350 feet in a few days is not inconsistent with figures cited by Williams (1932, pp. 141-142).

The extrusion of the first or outer dome in November may have been endogenous in the beginning, with the subsequent formation of a summit depression by collapse or explosion; it may have been entirely exogenous with a summit

crater continually present; or perhaps initially the dome was endogenous and later became exogenous. Insufficient data are available for a definite answer. Breadcrust bombs, blocks of crater lava, gas, and a little ash were expelled from the vent during the later stages.

In early December magma again rose in the conduit and formed a second or inner dome in the summit depression of the first. The inner dome also had a summit depression and was probably formed by exogenous growth. Later explosions or collapse may have tended to break up the viscous, partly solidified lava in the summit depression with the formation of block lava.

On December 8 lava broke through the base of Bárcena cone and flowed out to sea. This extrusion produced withdrawal of magma from the crater, which resulted in subsidence of the domes. However, the margin of the outer dome had solidified and consequently settled very little, if at all. It was left with prominent positive relief compared to the central part, which sagged and became saucer-shaped (Pl. XIII). (A similar origin is postulated for the depressed top of Cráter Herrera - figure 2). The minor scarp on the east side of the inner dome summit depression probably formed during this subsidence.

The break-up of the surface of the outer dome undoubtably took place before and during extrusion of the inner dome; the surface of the latter fragmented between December, 1952, and March, 1953.

Two primary solfataras developed large craterlets in the crater of Bárcena immediately south of the outer dome between November 15 and December 10, 1952. These remained active until about the fall of 1953.

Delta Lávico

General description.

Trachytic lava in the Delta Lávico is gradational between block lava and aa; it can be best described as scoriaceous block lava (Howel Williams, personal communication). Indi-

vidual blocks occur up to about 10 feet in size and usually have a conchoidal fracture (Pl. XXV). On the surface of the flow they are commonly only a few feet in diameter. The flow has recently been truncated by marine erosion. A gradation from the clinker phase of small fragmented blocks on top of the flow to the massive phase, which shows columnar jointing, is clearly shown in an enlargement of a photograph taken from the bridge of the R/V *Crest* in May, 1955 (Pl. XXVI). Also shown is an intermediate phase of small cobbles and boulders of block lava with smooth polyhedral faces which grade into partly detached boulders of block lava. Local areas of block lava also are found on the flow margin.

Surface lava in the flow is moderately vesicular; vesicles range from a few millimeters in diameter, normal to the direction of flow, to 3 or 4 cm parallel to the flow direction. Some of the more massive blocks, probably from the interior of the flow, are only slightly vesicular with a vesicle size usually less than 2 mm. A small, short flow south of the vent consists of spongy lava. Here gas-rich lava was extruded from near the top of the vent, flowed south, and reached the main flow at the lower edge of the vent. Lava from this flow has a pseudo-spinosity produced by a coalescence of inflated bubbles.

Movement.

Photographs taken from the sea and air in December, January, and April, after the formation of the flow, show that lava only issued from a single vent. Lava from the vent at first spread out in the shape of a fan with concentric flow lines (Pl. XVI). Later, tongues formed at the flow margin (Pl. XVIII, XIX). There was little development of moraines, because flow tongues did not form except at the margin where they tended to diverge from one another.

Lateral movement of the flow in December appeared to be similar to that illustrated by Krauskopf (1948, fig. 3). The conchoidal appearance of the large blocks in the flow (Pl. XXV) would result from the type of motion observed at Hekla and

described by EINARSSON (1949, pp. 26-30), who reports that the characteristic separation of the plastic blocks was a fracturing as if the material were solid.

Vent.

A photograph taken in November, 1953, shows the relation of the vent, the solfatara area above, and the scoriaceous block lava on the surface of the flow near the vent (Pl. XXVII). Sulfurous sublimation products from the solfatara immediately above the vent coated the side of the cone nearly 300 feet to either side of the depression area in March, 1953. A close-up of the mouth of the vent shows layers of lava deposited on the sides of the vent wall as the magma oozed out to form the delta (Pl. XXVIII). Four layers are shown. They are labeled 1-4 in this photograph. Two of these (1 and 2) slope relatively steeply and probably represent flow stages when the lava level in the vent was high and the altitude of the delta low. As the lava supplied from the vent diminished, the level of the flow gradually lowered and also tended to move in a more horizontal direction because of the greater height of the delta. Two layers (3 and 4) representing the last two lowerings can be seen on the left side of the photograph next to the flow surface. The lava blocks on the surface of the flow in the vent are larger and more angular than customarily found on the surface of the delta. They originate from the final fracturing of a very viscous, nearly solidified magma.

The mouth of the vent is not more than 10 feet wide. Although the sides of the vent appear to converge downward (Pl. XXVIII), in reality they may diverge below the surface of the flow. Regardless, the hydrostatic pressure was sufficient to extrude about 800 million cubic feet of visçous trachyte through the same hole.

Subsidence.

The maximum altitude of the surface of the Delta Lávico was determined to be 125 feet by altimetry on March 9, 1953 (Table 3). Photogrammetric measurements from the April 16

vertical air photographs indicate that the maximum height was greater than 108 feet. On the November, 1953, visit visual observation and crude measurements indicated to the writer that the flow was appreciably lower. A traverse of hand level measurements made in May, 1955, determined that the maximum altitude of the flow surface was about 75 feet. Clearly the Delta Lávico appears to have subsided 30 to 40 feet. The only other evidence of settling is from the altitude of the lava flow between the vent and delta. In March, 1953, there was a smooth slope from the flow in the vent to the delta; in November a relatively abrupt slope was present. There are no other visual indications of subsidence on the delta or to either side of the pumice beaches. However, material in these locations would be unlikely to show signs of this nature because of the covering effects produced by terrestrial erosion. It is not surprising that the delta would settle considering the effect of consolidation of the pyroclastics underneath the lava caused by an overburden of about 40 million metric tons of lava. (The latter figure was determined on the assumption that a cubic meter of lava weighs about 1.9 metric tons — FRIES, 1953, p. 609. It would represent an approximate average of nearly 60 metric tons per square meter of surface.)

Volume of erupted tephra and lava

Calculations have been made of the volume of tephra and lava erupted in the formation of Volcán Bárcena (Table 5). An estimation of the volume of tephra not contained in the cone is very difficult because much of the material fell into the sea; the figures given may be conservative. Areal dimensions were determined by planimetric measurement from a topographic map.

Approximately 9500 million cubic feet (270 million cubic meters) of tephra and 970 million cubic feet (27 million cubic meters) of lava were erupted. This is an order of magnitude less than the 2000 million cubic meters of material erupted in the formation of Parícutin Volcano (*cf.* FRIES, 1953, p. 611).

Table 5.

Area and volume of erupted tephra and lava from Volcán Bárcena.

Feature	Material	Area		Volume	
		million sq ft	thousand sq m	million cu ft	million cu m
Bárcena cone	Tephra	15 to 20	1400 to 1900	7000 to 11,000	200 to 310
Tephra not part of Bárcena cone	Tephra	—	—	100 to 1000	2.8 to 28
Crater dome (September 20, 1952)	Lava	0.025	2.3	0.02	0.0006
Outer crater dome (November 1952)	Lava	1.1	102	140	4
Inner crater dome (December 1952)	Lava	0.1	12	2	0.6
Delta Lávico (part of flow above sea level)	Lava	6.6	610	430	12.2
Delta Lávico (part of flow below sea level)	Lava	7.4	690	400	11.3

REFERENCES

BATES, D. H., 1952 - *Revilla Gigedo Islands, Mexico*: Portland. Privately published by the author, 44 pp.

BELL, H. S., 1942 - *Density currents as agents for transporting sediments*: Jour. Geol., vol. 50, pp. 512-547.

BEMMELEN, R. W., van, 1949 - *The geology of Indonesia*: The Hague, Govern. Print. Office, vol. 1A, 732 pp.

BISHOP, S. E., 1901 - *Brevity of tuff-cone eruptions*: Am. Geol., vol. 27, pp. 1-5.

BRATTSTROM, B. H., and HOWELL, T. R., 1956 - *The birds of the Revilla Gigedo Islands, Mexico*: Condor, vol. 58, pp. 107-120.

DAWSON, E. Y., 1954 - *The marine flora of Isla San Benedicto following the volcanic eruption of 1952-1953*: Univ. Southern Calif. Press, Allan Hancock Found. Publ., Occas. Paper 16, 13 pp.

DIETZ, R. S. (Ed. by D. C. Kelley), 1953 - *Boqueron*: Pacific Discovery, vol. 6, pp. 24-27.

———— and RICHARDS, A. F., 1953 - *Volcanic eruption of San Benedicto Island, Mexico* (Abstract): Geol. Soc. America Bull., vol. 64, p. 1503.

EINARSSON, T., 1949 - *The flowing lava: The eruption of Hekla 1947-1948*: Reykjavik, H. F. LEIFTUR (for the Soc. Scient. Islandica), vol. 4, no. 3, 70 pp.

FINCH, R. H., 1933 - *Block lava*: Jour. Geol., vol. 41, pp. 769-770.

———— and ANDERSON, C. A., 1930 - *The quartz basalt eruptions of cinder cone, Lassen Volcanic National Park, California*: Univ. Calif. Publ., Bull. Dept. Geol. Sci., vol. 19, pp. 245-273.

FOSHAG, W. F., and GONZÁLEZ R., J., 1956 - *Birth and development of Parícutin Volcano, Mexico*: U. S. Geol. Survey Bull. 965-D, pp. 355-489.

FRIES, C., Jr., 1953 - *Volumes and weights of pyroclastic material, lava, and water erupted by Parícutin Volcano, Michoacán, Mexico*: Am. Geophy. Union Trans., vol. 34, pp. 603-616.

HANNA, G. D., 1926 - *Expedition to the Revillagigedo Islands, Mexico, in 1925*: Calif. Acad. Sci. Proc., 4th ser., vol. 15, 113 pp.

KRAUSKOPF, K. B., 1948 - *Lava movement at Parícutin Volcano, Mexico*: Geol. Soc. America Bull., vol. 59, pp. 1267-1284.

LACROIX, A., 1904 - *La Montagne Pelée et ses Eruptions*: Paris, Masson et Cie, 662 pp.

———— 1906 - *Contribution à l'étude des brèches et des conglomérats volcaniques (Antilles 1902-1903, Vésuve 1906)*: Soc. Géol. France Bull., sér. 4, t. 6, pp. 636-685.

———— 1930 - *Remarques sur les matériaux de projection des*

volcans et sur la genèse des roches pyroclastiques qu'ils constituent: Soc. Géol. France Cent., Livre Jubilaire 1830-1930, t. 2, pp. 431-472.

MacGregor, A. G., 1952 - *Eruptive mechanisms: Mt. Pelée, the Soufrière of St. Vincent and the Valley of Ten Thousand Smokes*: Bull. Volc., sér. 2, t. 12, pp. 49-74.

———— 1955 - *Classification of nuée ardente eruptions*: Bull. Volc., sér. 2, t. 16, pp. 3-5.

Mason, H. L., 1953 - *Land plants, Isla San Benedicto*, in Richards, A. F. (Ed.) *The Islas Revillagigedo investigation of November 1953*: Unpubl. manuscript.

McNeil, G. T., 1952 - *Map compilation with stereometer-type instruments*, pp. 603-622 in *Manual of photogrammetry*: Washington, Am. Soc. Photogrammetry, 2nd ed., 876 pp.

Menard, H. W., 1955 - *Deformation of the northeastern Pacific basin and the west coast of North America*: Geol. Soc. America Bull., vol. 66, pp. 1149-1198.

Perret, F. A., 1924 - *The Vesuvius eruption of 1906, study of a volcanic cycle*: Carnegie Inst. Washington, Publ. 339, 151 pp.

———— 1937 - *The eruption of Mt. Pelée 1929-1932*: Carnegie Inst. Washington, Publ. 458, 126 pp.

Richards, A. F., 1953 - *Continued volcanic activity at San Benedicto Island, Mexico*: Volcano Letter, no. 519, p. 7.

———— 1956 - *Volcanism in eastern Pacific Ocean basin: 1945-1955*: Unpubl. manuscript.

———— 1957 - *Geology of the Islas Revillagigedo, Mexico* (Abstract): Geol. Soc. America Bull., vol. 68, p. 1843.

———— 1958 - *Transpacific distribution of floating pumice from Isla San Benedicto, Mexico*: Deep-sea Res., vol. 5, pp. 29-35.

———— and Brattstrom, B. H., 1959 - *Bibliography, cartography, discovery, and exploration of the Islas Revillagigedo*: Calif. Acad. Sci. Proc., 4th ser., vol. 29, pp. 315-360.

———— and Dietz, R. S., 1956 - *Eruption of Bárcena Volcano, San Benedicto Island, Mexico*: Eighth Pacific Sci. Congr. Proc., vol. 2, pp. 157-176.

———— and Walker, L. W., 1954 - *Operation cremation*: Nat. Hist., vol. 63, pp. 56-64.

Rittmann, A., 1936 - *Vulkane und ihre Tätigkeit*: Stuttgart, Ferdinand Enke, 188 pp.

Sapper, K., 1937 - *Mittelamerika: Handbuch der regionalen Geologie*: Heidelberg, Carl Winter's Universit., Bd. 8, Abt. 4a, 160 pp.

Snodgrass, J. M., and Richards, A. F., 1956 - *Observations of underwater volcanic acoustics at Bárcena Volcano, San Benedicto Island, Mexico, and in Shelikof Strait, Alaska*: Am. Geoph. Union Trans., vol. 37, pp. 97-104.

Stearns, H. T., and Vaksvik, K. N., 1935 - *Geology and ground-water resources of the island of Oahu, Hawaii*: Hawaiian Div. Hydrography Bull. 1, 479 pp.

Thorarinsson, S., 1944 - *Tefrokronologiska studier på Island*: Geog. Ann., vol. 26, 217 pp. (English summary: *Tephrochronological studies in Iceland*, pp. 204-215).

———— 1956 - *On the rhyolitic volcanic eruption in Iceland in post glacial time* (Abstract): Resumes Trabajos Pres., XX Intern. Geol. Congr., Mexico, p. 20.

U. S. Government Printing Office, 1950 - *The effects of atomic weapons*: Washington, 456 pp.

U. S. Navy Hydrographic Office, 1952 - *Volcanic activity north Pacific*: Hydrographic Bull., no. 32, August 9.

Washington, N. S., 1926 - *Santorini eruption of 1925*: Geol. Soc. America Bull., vol. 37, pp. 349-384.

Williams, H., 1932 - *The history and character of volcanic domes*: Univ. Calif. Publ., Bull. Dept. Geol. Sci., vol. 21, pp. 51-146.

———— 1952 - *Recent eruptions on San Benedicto Island, Mexico*: Volcano Letter, no. 517, p. 7.

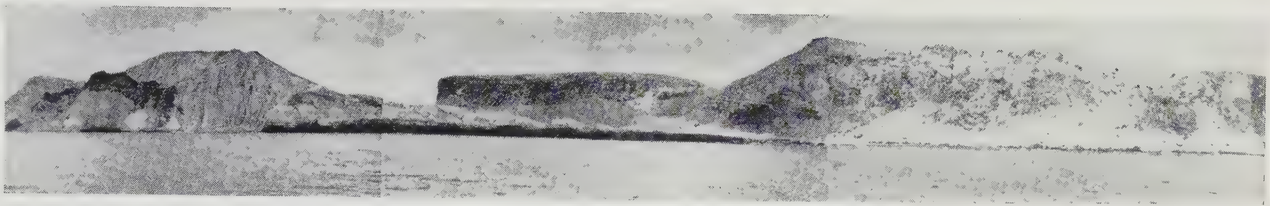
———— 1957 - *Glowing avalanche deposits of the Sudbury Basin*: Ontario Dept. Mines, 65th Ann. Rept., vol. 65, pp. 57-89.

Wolff, F., von, 1914 - *Der Vulkanismus*: Stuttgart, Ferdinand Enke, Bd. 1, 711 pp.

Zeller, E. J., 1953 - *Geochemistry, Isla San Benedicto*, in Richards, A. F. (Ed.) *The Islas Revillagigedo investigation of November 1953*: Unpubl. manuscript.

North flank of the eroded pyroclastic cone Montículo Cinerítico Probable location of Bárcena vent indicated by an X.

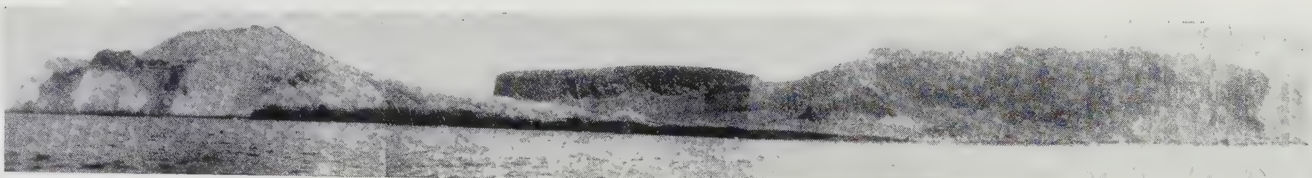
(California Academy of Sciences photo)



Panorama of southeastern Isla San Benedicto before the eruption of Bárcena.

Fig. 1. - February-March, 1952.

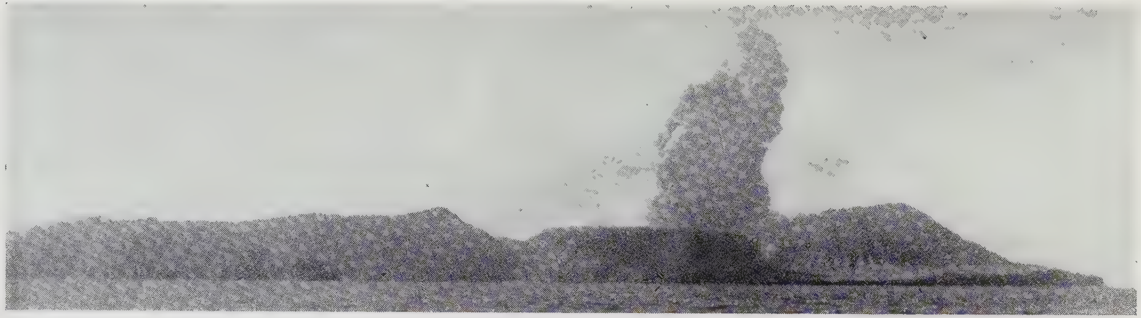
(D. H. BATES photo)



Panorama of southeastern Isla San Benedicto before the eruption of Bárcena.

Fig. 2. - May, 1925.

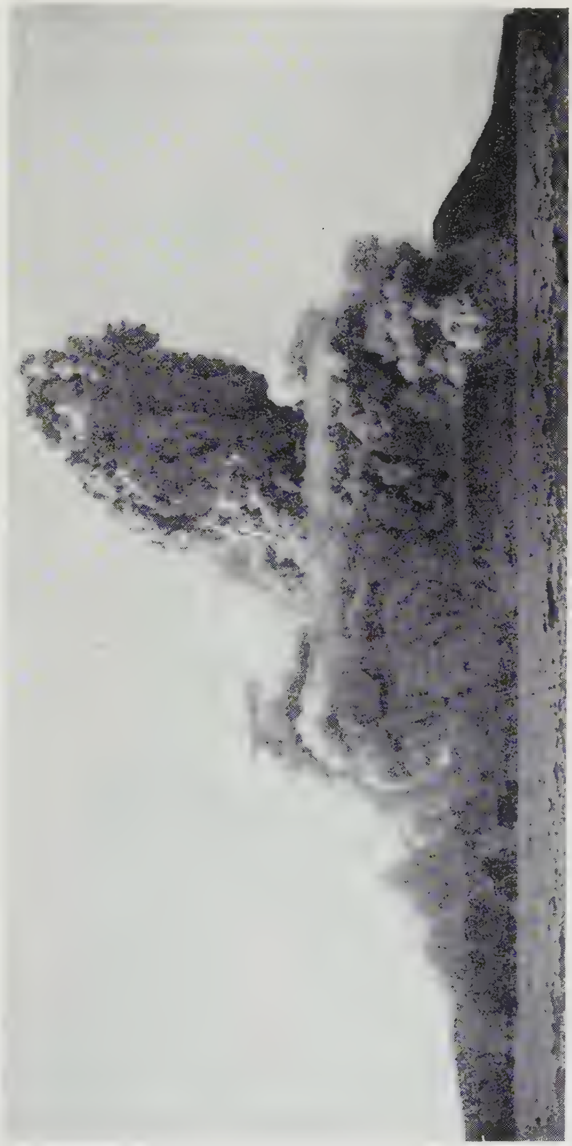
(California Academy of Sciences photo)



Birth of Volcán Bárcena.

Photograph taken from 2 miles west of Isla San Benedicto at 0745 on August 1, 1952. Cráter Herrera, left; Roca Challenger, center; Montículo Cinerítico, right.

(R. Petrie photo)



Birth of Volcán Bárcena.

A few minutes later.

(R Petrie photo)

Birth of Volcán Bárcena

About 0805.

(R. Perez photo)

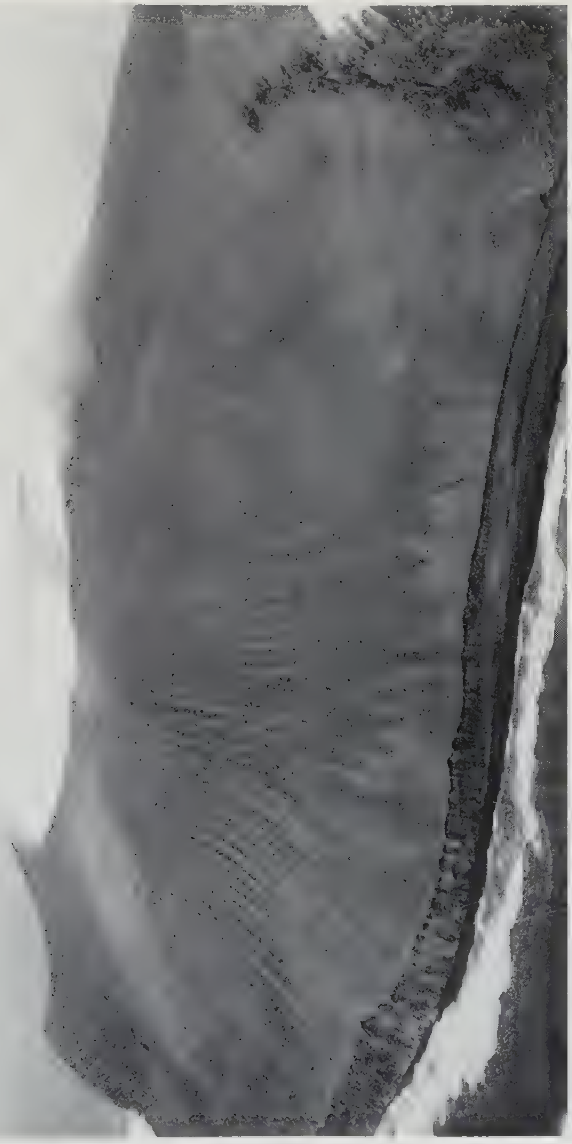
August, 1952, eruption of Bárcena.

Volcanic density flow (tephra avalanche) of August 12, on Bárcena cone. Crater rim upper left corner, south side of Cráter Herrera extreme right center. Untouched enlargement from a 16 mm duplicate Kodachrome motion picture frame.

(T. HOWELL photo)

Bárcena in eruption September 12, 1952.
Weak vulcanian-type eruption.

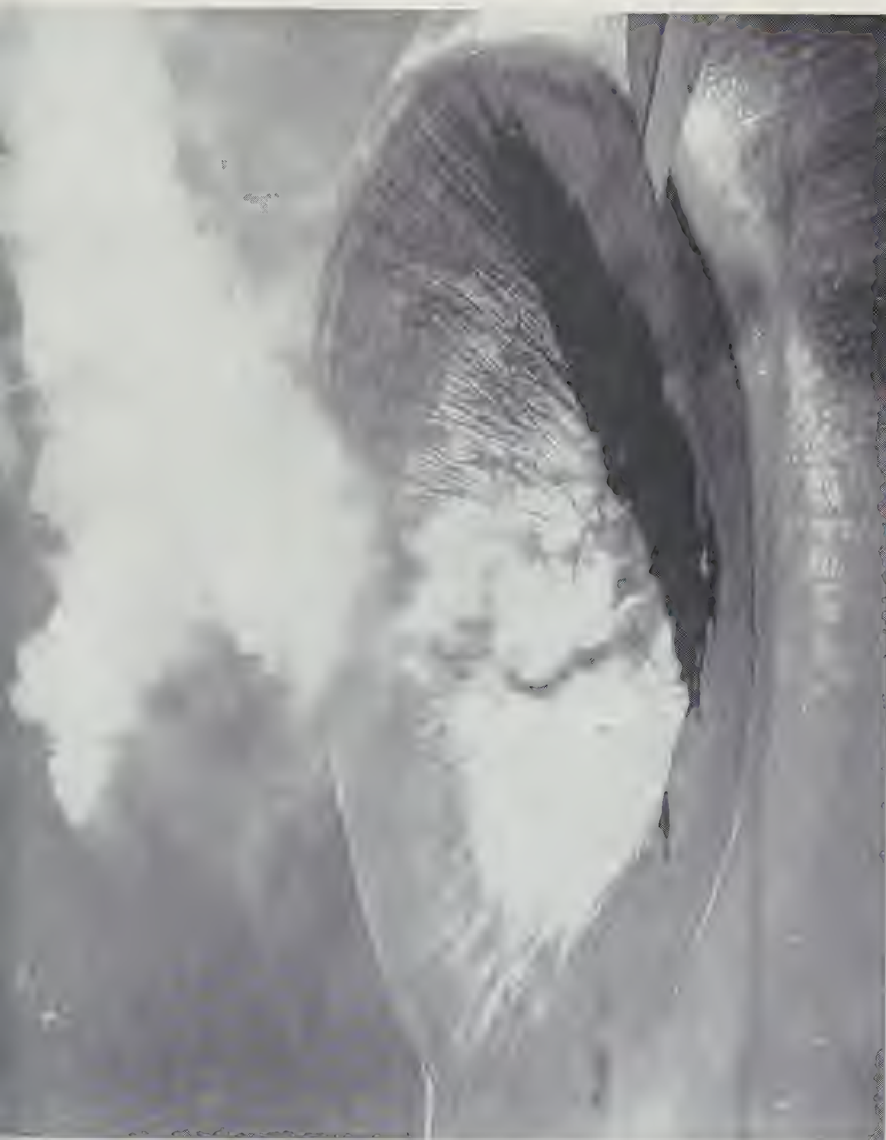
(U. S. Navy photo)



Bárcena in eruption September 12, 1952.

Furrows on east flank. Cráter Herrera extreme right.

(U. S. Navy photo)



September 20, 1952. Steam issues from proto-dome. Wing of plane points to the terrace on the west side of the crater.
(U. S. Navy photo)

Bárcena crater dome.

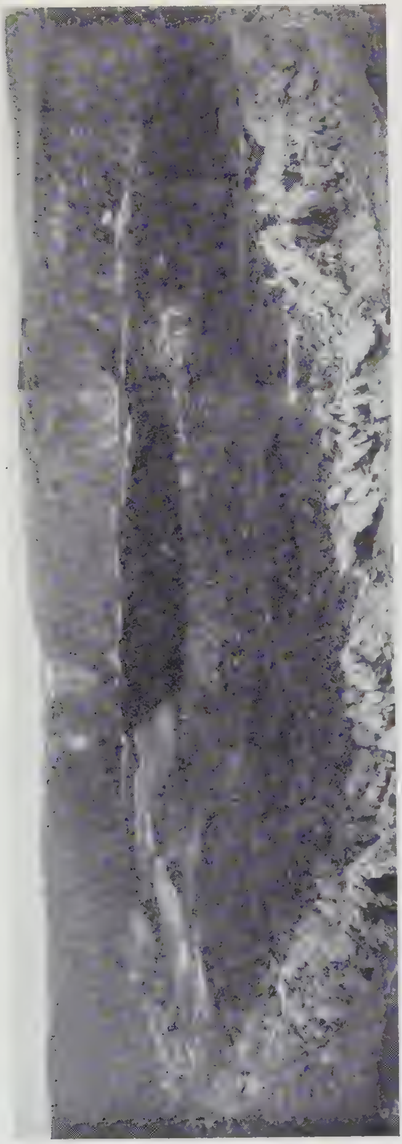
November 15 1952 Viscous trachyte lava half-fills the crater. Montículo Cinerítico in left background.
(U. S. Navy photo)

Rin of Bárcena crater.

South or leeward side Note the graben in the rim, top slightly left of center. December 10, 1952.
(L. W. Walker photo)

Bárcena crater.

Steam eruption from the annular depression or « moat » between the inner and outer domes. December 10, 1952.
(L. W. Walker photo)



Bárcena crater in November, 1953. The crater wall is about 200 feet high above the dome. Raised edge of the dome in the foreground is about 40 feet high.

(A. F. RICHARDS photo)

Eruption of Bárcena from the sea.

Eruption of December 12, 1952, photographed from the M/V *Southern Queen*. Delta Lávico at lower left.
(L. W. Walker photo)

Eruption of Bárcena from the sea.

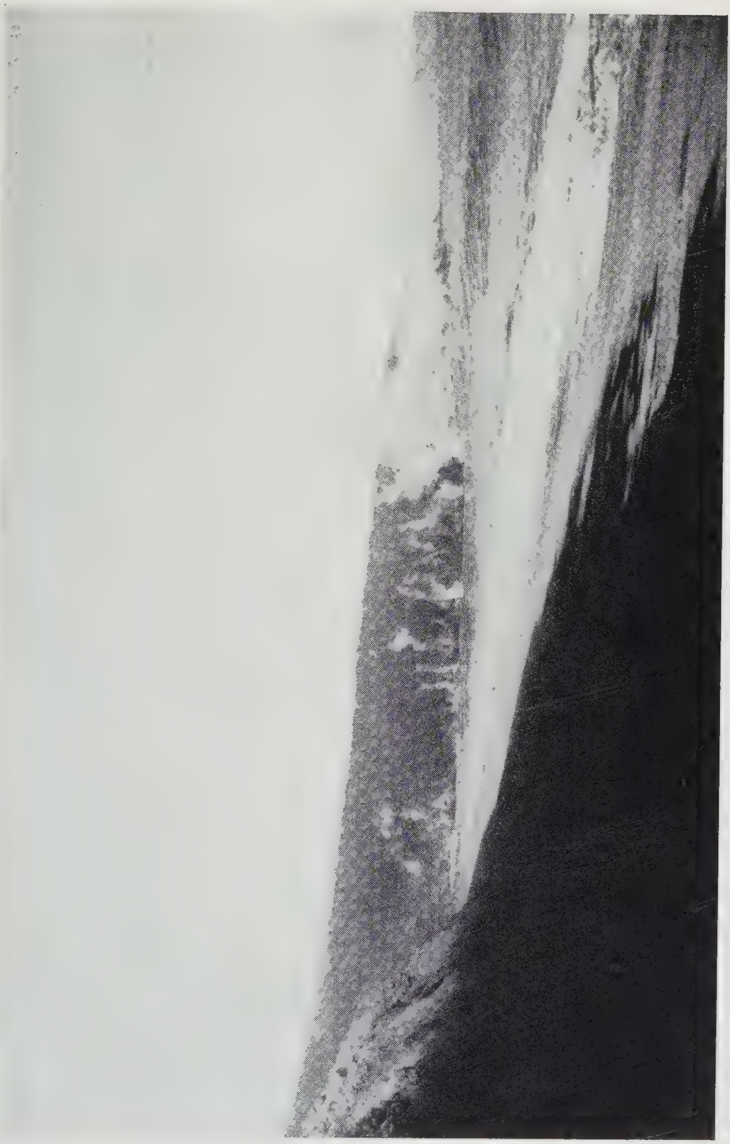
Delta Lávico and Volcán Bárcena on December 9 from the yacht *Observer*. Steam from the seaward margin of the flow, darker gas from the vent. Note graben in the crater rim.

(L. W. WALKER photo)

Delta Lávico.

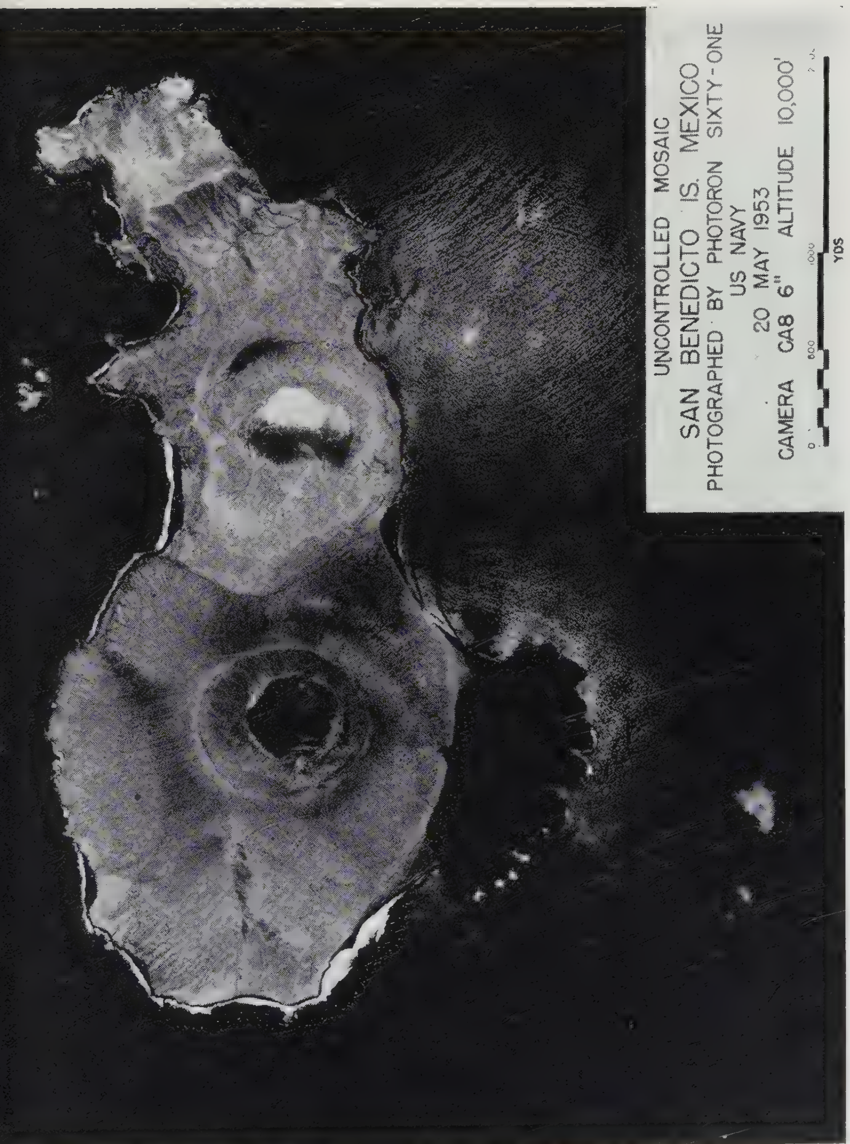
Delta Lávico from the air on December 11, 1952. View looking north. Seaward extent of flow 900 feet, width about 1100 feet.

(A. F. RICHARDS photo)



Delta Lávico.

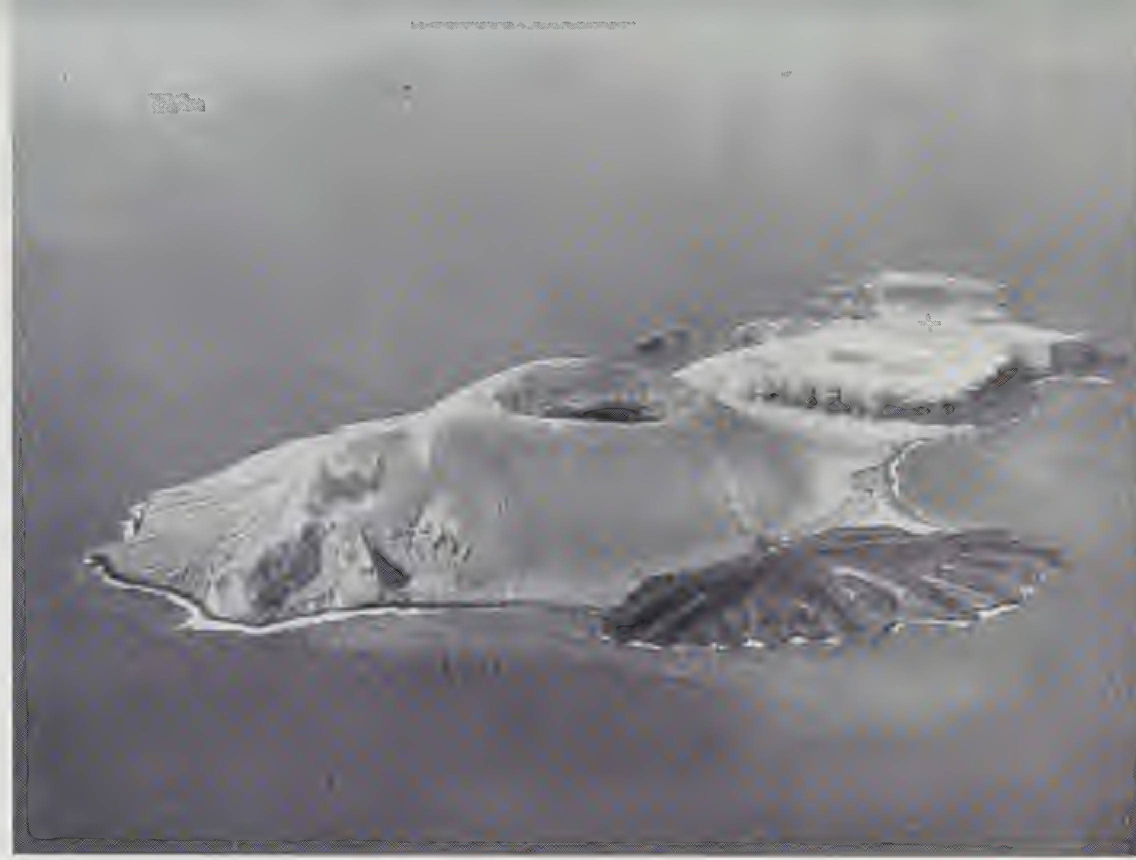
Profile of flow from Volteadura Beach on December 11. Seaward slope of flow about 14°.
(L. W. WALKER photo)



Isla San Benedicto from the air.

Mosaic of island before erosion of the Delta Lávico. Dark areas on the delta represent the last flows of lava. Note the two solfatara craterlets in Bárcena crater. The white area in Cráter Herrera is a playa deposit of very fine-grained tephra washed from the walls of the crater, which is a basin of internal drainage.

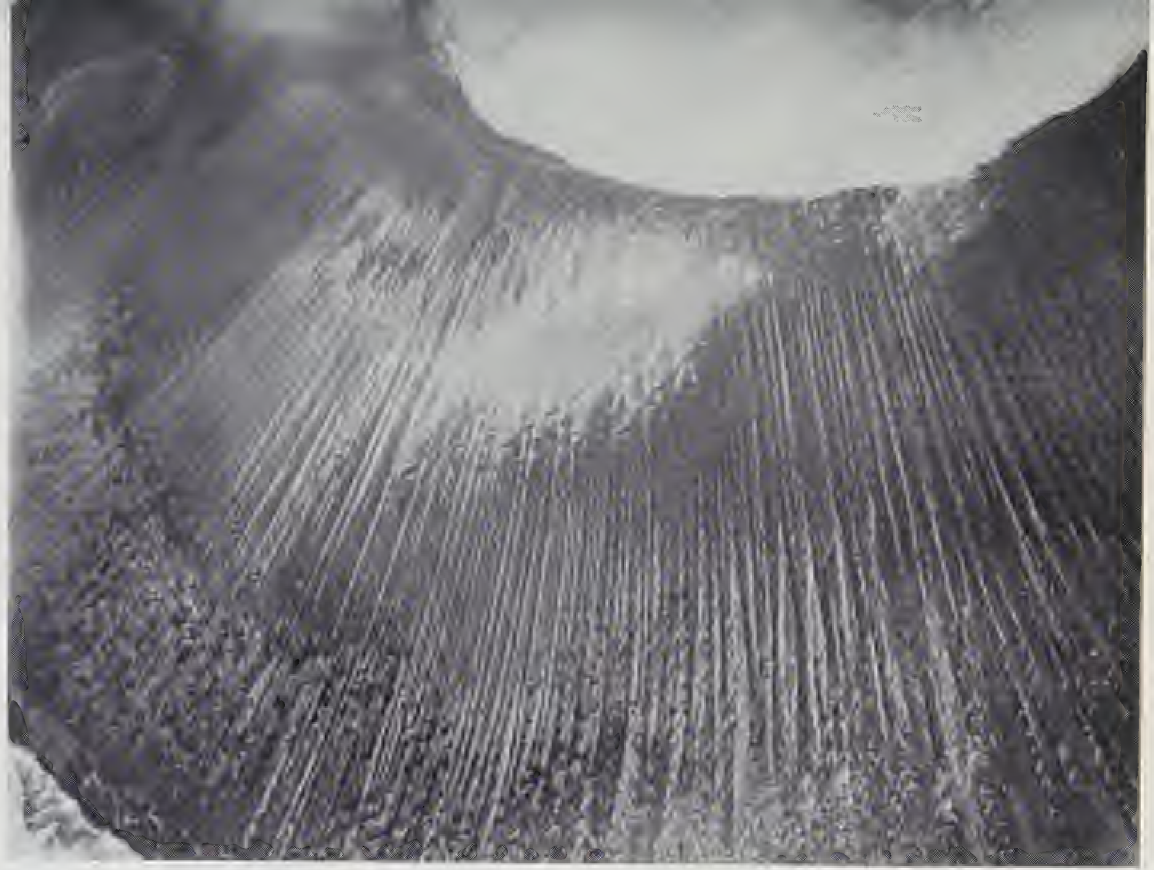
(U. S. Navy mosaic)



Isla San Benedicto from the air.

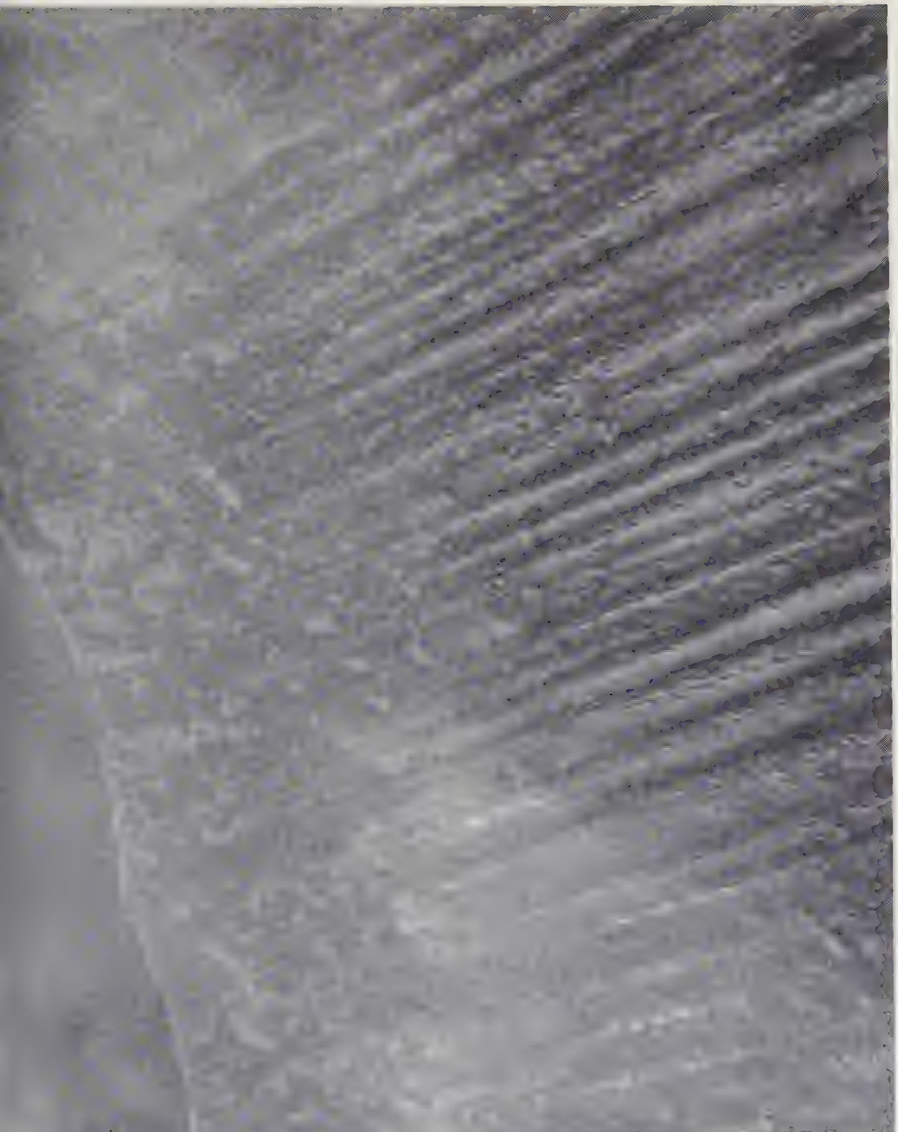
Oblique air photograph taken in March, 1953. Montículo Cinerítico to left of Bárcena. Cráter Herrera to right. Note that wave erosion has truncated the ends of the flow tongues and has tended to fill the indentations between tongues.

(A. F. Richards photo)



Furrows on the east flank of Bárcena, September 12, 1952. The sea cliff and ocean are shown in the lower left corner. The light-colored areas represent recent deposits of ash. Photographs in Plates XXI and XXII are taken to the right of the largest fresh deposit of ash.

(U. S. Navy photo)



Furrow detail on the east flank of Bárcena

Upper ends of the furrows.

U. S. Navy photo

Furrow detail on the east flank of Bárcena.

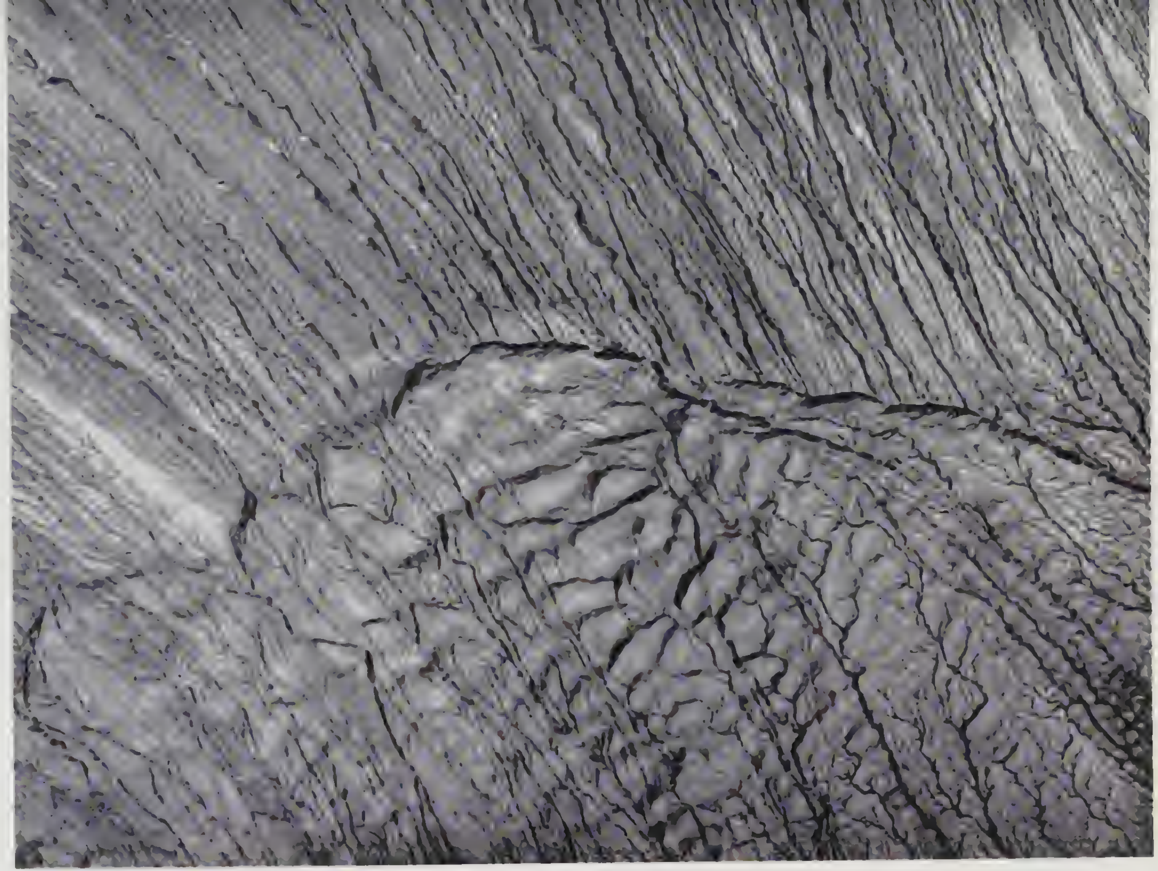
Lower end of the furrows almost directly below Plate XXI.

(U. S. Navy photo)

Furrows on the west flank of Bárcena, September 20, 1952.

General view. Crater rim in upper left corner. Note absence of straight-type furrows on Monticulo Cinerítico (to right). The furrows on Bárcena (to left) have been modified by rains subsequent to their formation.

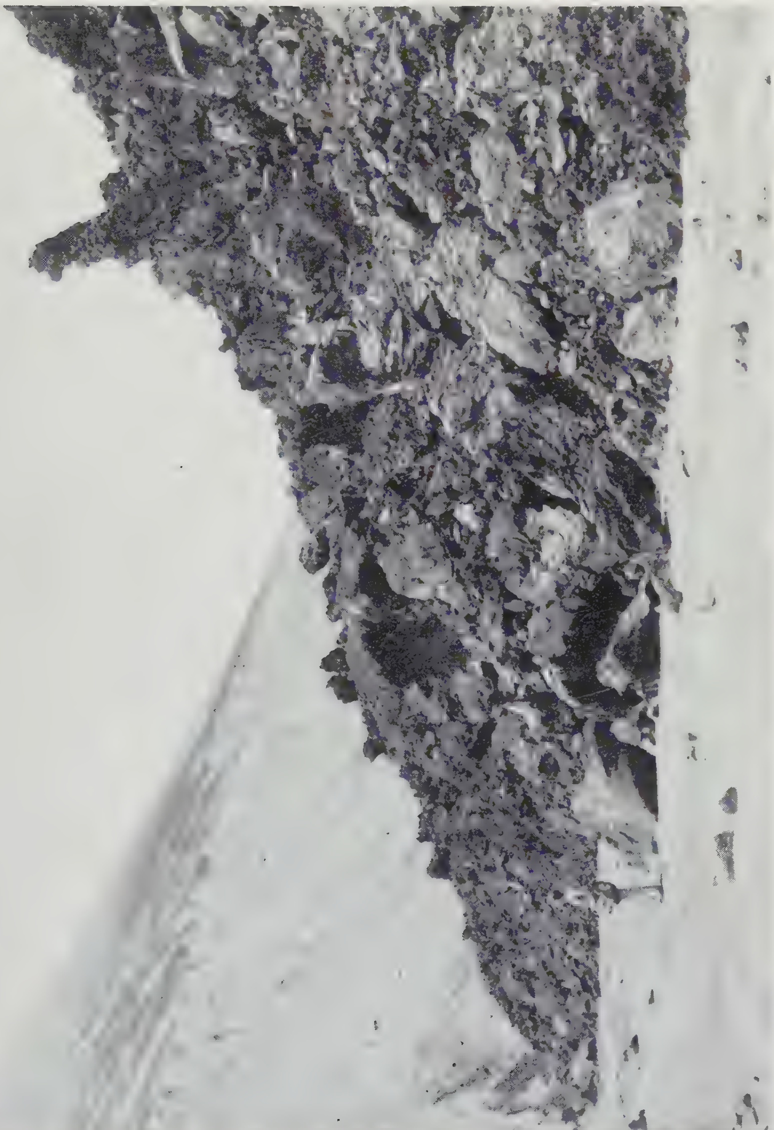
(U. S. Navy photo)



Furrows on the west flank of Bárcena, September 20, 1952

Close-up of the peculiar topography shown in the center of Plate XXIII. The pattern in the ash is believed to have been caused by tephra avalanches when they encountered the abrupt change of slope in this area. This pattern does not appear to be related to any pre-eruption buried topography.

(U. S. Navy photo)



Structure of the Delta Lávico, in May, 1955.

Side of the scoriaceous block lava flow facing Volteadura Beach. Note the conchoidal fracture of the larger blocks.
(R. GILMORE photo)

Structure of the Delta Lávico, in May, 1955.

Cross-section of a flow tongue which has been truncated by wave erosion. Scoriaceous clinker on the top grades to massive lava in the flow interior, which shows columnar jointing. Diagonal line to the left is part of the rigging of the R/V *Crest.*

(R. GILMORE photo)

Delta Lávico vent in November, 1953.

General view from the top of the delta. Solfatara depression in the side of the cone above the vent is indicated by an arrow.

(A. F. Richards photo)

Delta Lávico vent in November, 1953.

Mouth of the vent. Four stages of the flow are labeled on the side of the vent to the eft. The light-colored area above the vent is the solfatara depression.

(A. F. Richards photo)

G. IMBÒ

Quelques considérations sur la tension magmatique et sur la " température d' irrigidimento „

(Avec 7 figures)

La présence des composants volatils en solution et à l'état libre confère aux magmas le caractère d'émulsion gazeuse, à laquelle correspond, par rapport à des paramètres caractéristiques, une valeur particulière de la pression, dite tension magmatique. Le rapport entre la masse de substances volatiles en solution et celle à l'état libre est réglé par la loi de Henry. L'application de la loi caractéristique des gaz permet de déduire, en cas de magma surchauffé, l'existence d'une proportionalité entre la tension et la température absolue. On constate partant dans le cas susdit, au cours du refroidissement magmatique, une réduction progressive de la tension. La réduction se poursuit de façon linéaire jusqu'à la phase initiale de formation des cristaux ou au point terminal de l'intervalle de fusion.

La diminution ultérieure de température donne lieu à une discontinuité de la courbe, laquelle représente la variation de la tension en fonction de la température.

L'étude de la variation de pression durant la formation de la phase solide exige évidemment la connaissance des modalités de la séparation. La complexité du phénomène et l'absence d'une loi analytique unique qui donne la variation de la masse cristallisée en fonction de la température, amènent nécessairement à subdiviser le champ thermique de fusion en petits intervalles à l'intérieur desquels on peut tenir pour admise l'absence de discontinuité. On admet en outre que le coefficient de solubilité est égal à 1 et que les cristaux ne contiennent pas de composants volatils.

On en vient ainsi à établir une loi générale réglant la variation de pression en fonction de la température, loi exprimée par la relation:

$$\frac{p}{T^{1-a}} = c.$$

La valeur de la constante c peut être donnée par les valeurs p_i et T_i relatives au point inizial de chacun des intervalles.

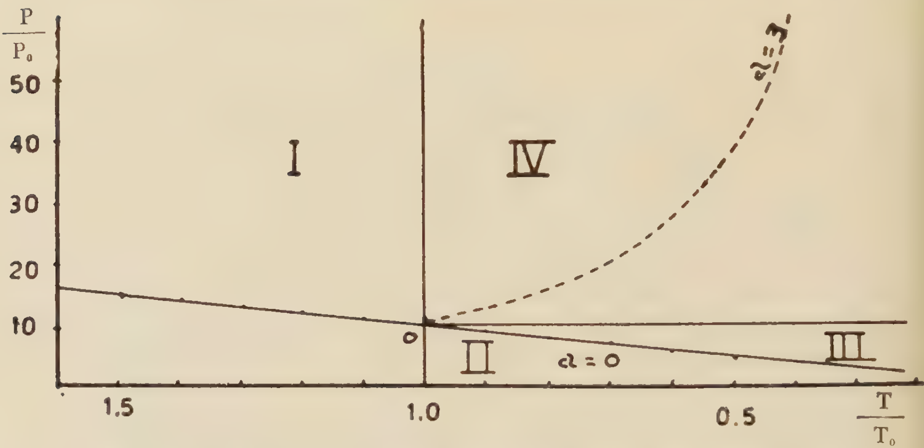


Fig. 1. - Variation de la pression en fonction de la température. On a indiqué sur les ordonnées le rapport p/p_0 et sur les abscisses le rapport T/T_0.

L'autre constante (a) qui figure dans l'exposant de T tient compte des modalités de la séparation de la phase solide.

Pour $a = 0$, le comportement est analogue à celui qui caractérise le stade de surchauffe, à savoir le simple rapport pression-température.

Pour $a = 1$, on a affaire par contre à une pression constante dans l'intervalle considéré.

Dans le plan p, T (fig. 1) on peut partant distinguer quatre régions, correspondant à quatre comportements distincts. Au lieu d'indiquer dans la figure les valeurs de p et T, on a adopté les valeurs des rapports p/p_0 et de T/T_0, où p_0 et T_0 représentent les valeurs de la pression et de la

température au stade initial de la formation de cristaux ou au point initial de chacun des intervalles partageant le champ thermique caractéristique du passage ainsi considéré d'un état à l'autre. Ces points ont pour coordonnées: *I, I.* La ligne parallèle à l'axe des ordonnées, et dont l'abscisse est égale à 1, partage le cadran et deux zones, correspondant à des valeurs d'abscisses respectivement supérieures et inférieures

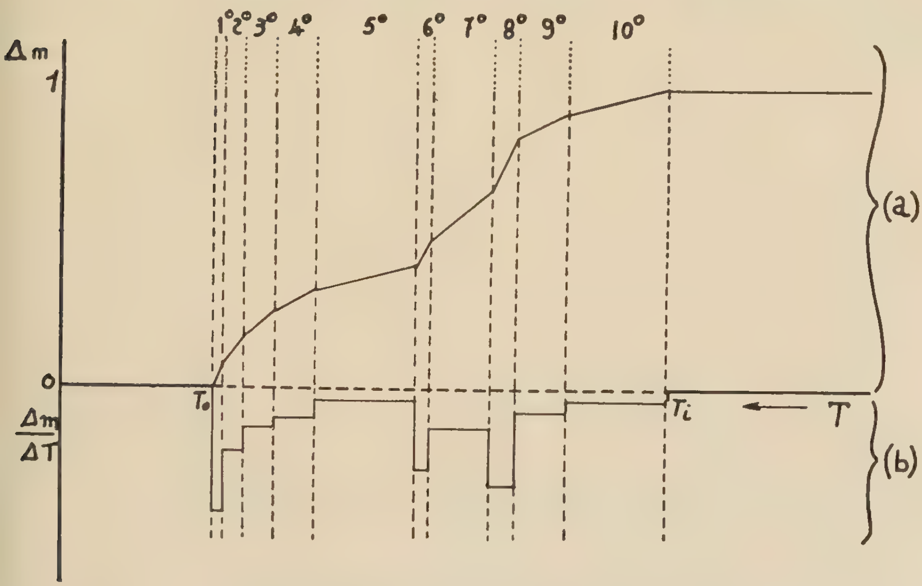


Fig. 2. - Variation hypothétique de la masse de cristaux (Δ m) en cours de refroidissement. On a indiqué aussi la variation unitaire $(\frac{\Delta\ m}{\Delta\ T})$ de la masse.

à 1. Au cas où le point considéré correspond au point initial du champ thermique de formation des cristaux, dans la zone correspondant à des abscisses supérieures à l'unité (région I), peut être représenté analytiquement le rapport pression-température en cas de magma surchauffé. La zone correspondant par contre à des valeurs d'abscisses inférieures à l'unité, est subdivisée par les demi-droites $a = 1$ et $a = 0$ dans les autres régions, correspondant respectivement: à des valeurs de a comprises entre 0 et 1 (III), à des valeurs supérieures à 1

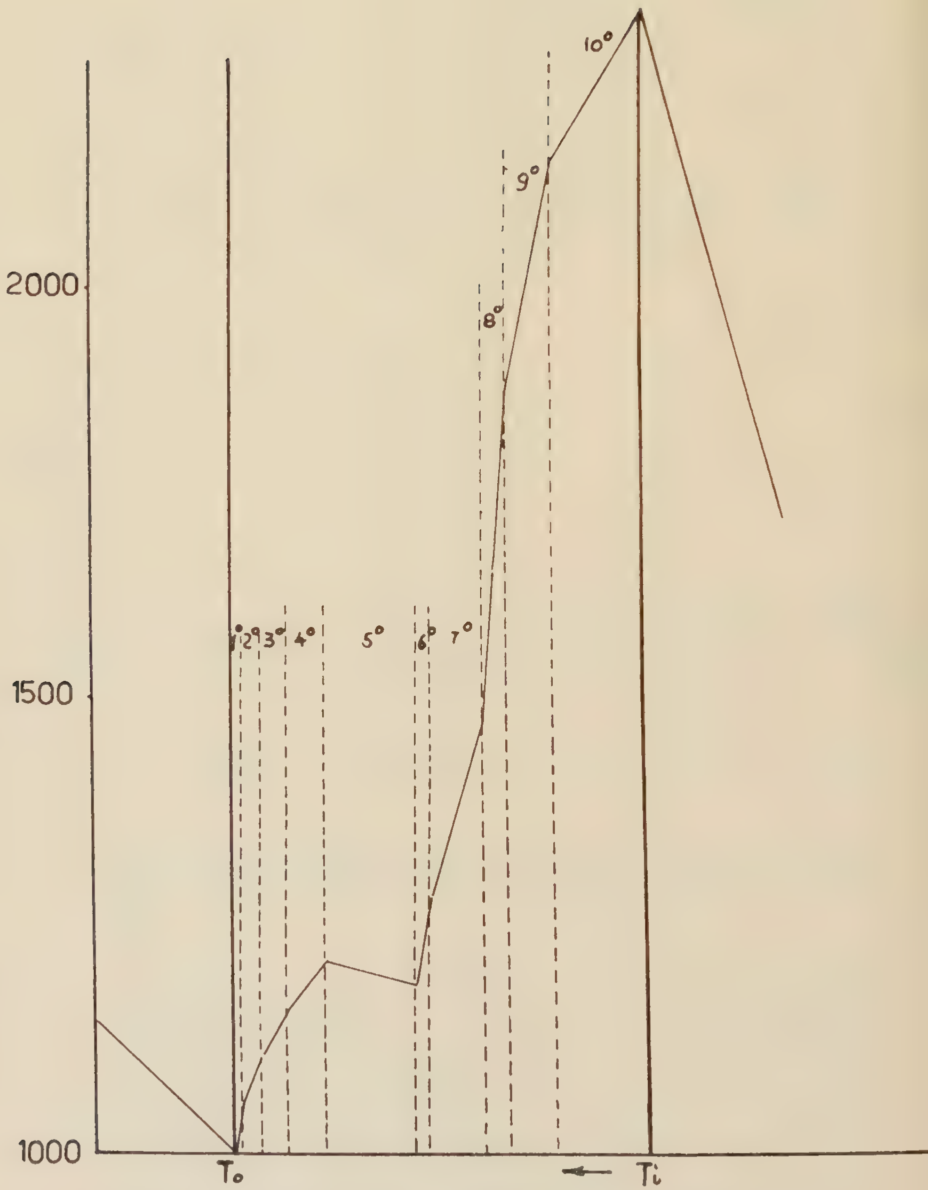


Fig. 3. - Variation de la tension magmatique correspondante à la variation dans la masse de cristaux, indiquée dans la fig. 2.

(IV), à des valeurs inférieures à 0 (II). La région III correspond à des valeurs de a qui déterminent une réduction de pression plus lente que celle correspondant au stade de magma surchauffé. La région IV correspond au contraire à des valeurs de a qui déterminent une augmentation de la pression. On a affaire à des valeurs négatives de a en cas de phénomène de réabsorption, c'est-à-dire de retour à l'état liquide primitif. A titre d'exemple, on a envisagé la variation

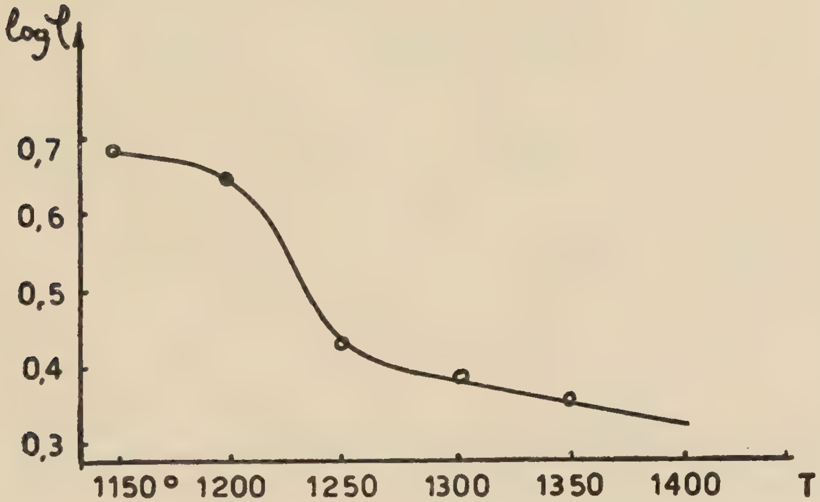


Fig. 4. - Coefficient de viscosité (η) - température (T) pour des laves andésitiques (Kani). On a indiqué sur les ordonnées la valeur: $\log \log\eta = \log\varphi$.

hypothétique dans la masse de cristaux qui se séparent du magma en cours de refroidissement, et dont la courbe a été représentée dans la fig. 2. Celle-ci permet de constater que la masse de cristaux est nulle jusqu'au point terminal du champ de fusion, alors que par la suite elle va sans cesse croissant et subit des variations irrégulières. Le champ de formation des cristaux a été subdivisé en dix sections, dans chacune desquelles la loi de variation de la masse en fonction de la température suit approximativement une ligne droite. L'application de la méthode exposée ci-dessus permet de déduire la courbe correspondante de la tension magmatique

(fig. 3). On relève l'existence de maximums et de minimums. Le maximum le plus élevé de la pression atteint une valeur qui est supérieure au double de celle (p_0) correspondant à la cessation du stade de surchauffe, à savoir:

$$\frac{p}{p_0} = 2{,}295.$$

L'achèvement du processus de formation des cristaux ou du passage d'un état à l'autre détermine le retour à la loi

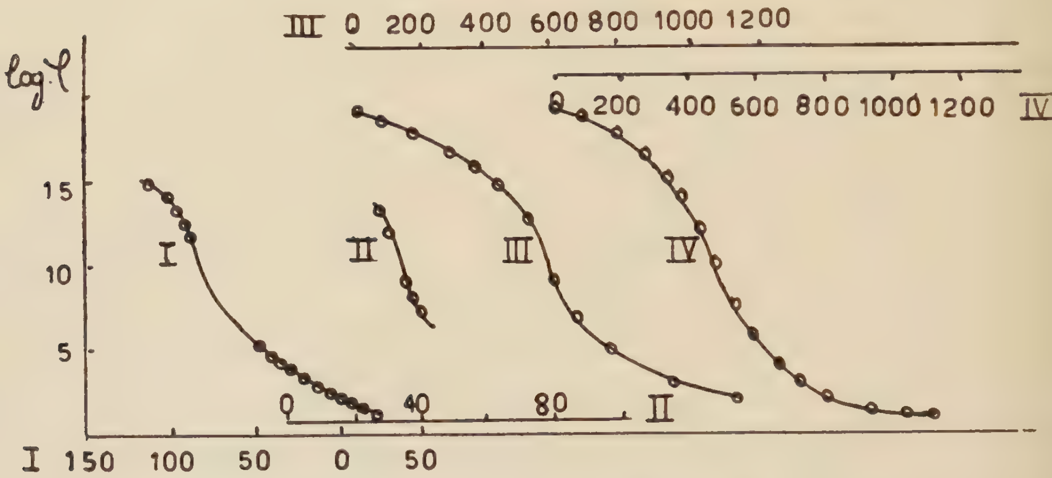


Fig. 5. - Courbes de viscosité pour quatre verres différents (I: verre de glycerine; II: verre de sélénium pur; III: verre sodocalcique; IV: verre au plombe); (WINTER).

de la simple proportionnalité ($a = 0$). En cas de refroidissement poussé, la cessation du processus se vérifie à une température à laquelle le coefficient de viscosité a atteint une valeur telle qu'elle empêche le mouvement moléculaire nécessaire à la formation des cristaux. Quelques expériences de laboratoire, effectuées sur des laves (fig. 4) et des substances vitreuses (fig. 5), ont permis de relever, dans les courbes température-coefficient de viscosité, l'existence d'un trait à variation rapide. On observe que le champ de variation du coefficient de viscosité, à l'intérieur duquel s'opère la variation rapide, est toujours le même, alors que le champ ther-

mique apparaît par contre variable. Si l'on étend cette considération à des masses ignées, on en déduit qu'un déplacement vers les températures relativement basses du champ thermique à l'intérieur duquel se produit la variation rapide

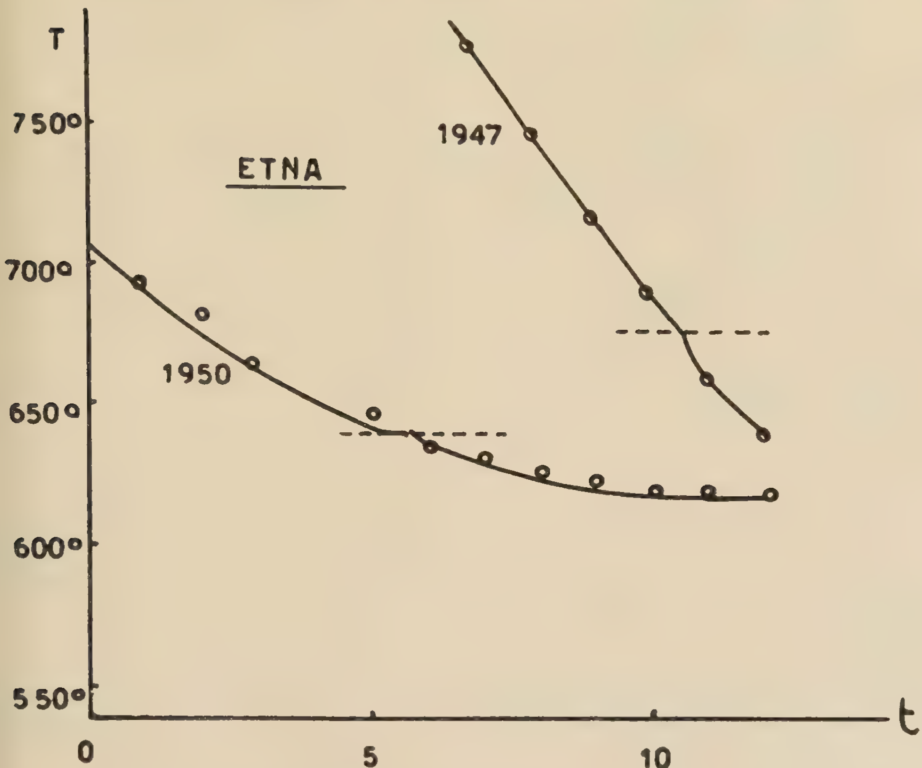


Fig. 6. - Courbes température - temp pour des laves de l'Etna.

du coefficient de viscosité, indique qu'on a affaire à un magma à bas coefficient de viscosité. Etant donné l'intervalle restreint, on considère la température moyenne qui a été dénommée «temperatura d'irrigidimento » Celle-ci est déduite des analyses thermiques et correspond à la discontinuité des courbes: température-temps, qui se manifeste à la plus basse température. Les figures (6, 7) représentent quelques analiyses thermiques effectuées sur des produits d'éruption de l'Etna (fig. 6) et du Vésuve (fig. 7). On observe une variation par rapport

aux conditions caractéristiques moyennes du volcan lors de l'operation, ainsi qu'aux phases particuliéres relatives aux produits examinés. La température moyenne des « températures d'irrigidimento » pour les produits de l'Etna (∾ 650°) est inférieure à la température relative aux produits du Vésuve (∾ 800°). On relève en outre, en ce qui concerne l'Etna, une différence des températures d'irrigidimento relatives à des laves du

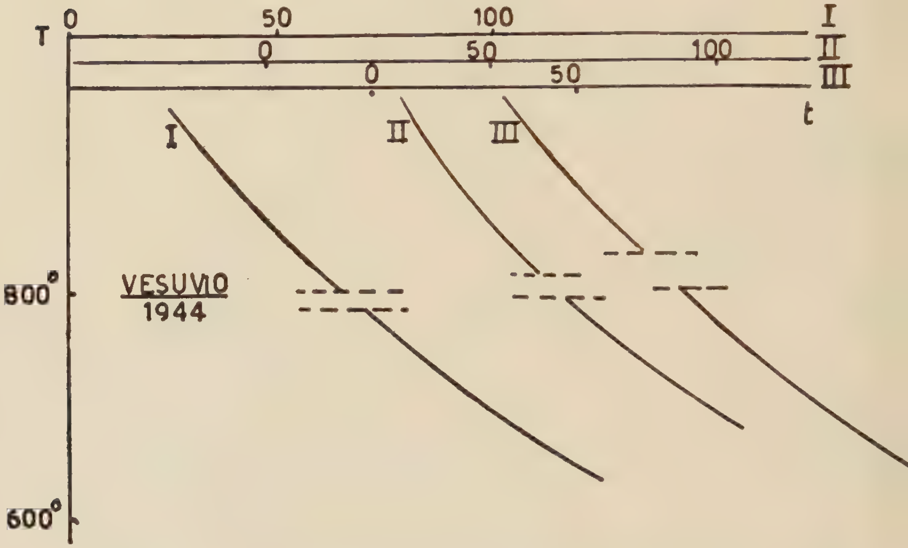


Fig. 7. - Courbes température - temp pour des produits émis au cours de l'éruptiohn de 1944.

1947 (∾ 670°) et du 1950 (∾ 635°). La diversité des valeurs justifie la diversité des caractères éruptifs des deux éruptions. Pour le Vésuve, on a pu constater au cours de l'éruption de 1944 une augmentation progressive de la température de pseudo-solidification. La valeur la pus basse (∾ 790°) se rapoprte à la phase d'écoulement de la lave, et la plus haute (∾ 820°) aux dernières phases, caractérisées par des phénomènes explosifs et notamment par la projection de matériaux non-incandescents.

Partant, la connaissance de la température d'irrigidimento acquiert une importance considérable: cette tempé-

rature, du fait qu'elle permet de déduire le coefficient de viscosité ou qu'elle en représente du moins un indice, revêt le caractère de paramètre dynamique.

Cette considération conclut en fait la digression relative à la température d'irrigidimento, laquelle, en vérité, représente dans quelques cas seulement, l'extrême inférieur de l'intervalle à l'interieur duquel se produit la formation de cristaux. Pour ce qui est de la première partie de cet exposé, à savoir la courbe de la pression magmatique sous l'influence de la température, nous avons déjà clairement indiqué les principales déductions. Nous jugeons cependant utile, compte tenu des considérations effectuées ci-dessus, de souligner la possibilité d'énoncer des lois qui intéressent la dynamique du volcanisme, lois plus étendues que celles prévues par Niggli, qui, se plaçant sur le plan qualitatif, a considéré seulement un aspect particulier du phénomène.

B. GÈZE, H. HUDELEY, P. VINCENT, Ph. WACRENIER

Les volcans du Tibesti (Sahara du Tchad)

(Avec 5 figs. dans le texte, 16 planches et 1 carte)

I. - Introduction

Situé à l'extrême Nord de l'Afrique Equatoriale Française, à égale distance de la Méditerranée et du lac Tchad, le massif montagneux du Tibesti s'étend du 19e au 22e degré de latitude Nord et du 16e au 19e degré de longitude Est. D'une superficie voisine de 100.000 km², il est revêtu, sur le tiers de sa surface environ, par un épais manteau de formations volcaniques qui forment les plus hauts sommets.

La nature des principales roches composant ce massif nous était déjà bien connue grâce à l'étude faite par A. Lacroix sur des échantillons ramenés par les missions du Général J. Tilho, de M. Dalloni et du Lieutenant-Colonel de Burthe d'Annelet (1).

Dans le cadre de la mission de reconnaissance géologique et minière des territoires de Borkou-Ennedi-Tibesti, organisée par la Direction des Mines et de la Géologie de l'A.E.F., nous avons, de Décembre 1956 à Mars 1957, essayé de dégager les principaux caractères du massif volcanique. Les études faites sur le terrain ont été complétées par une interprétation photogéologique qui a permis de dresser une esquisse géologique de cette région. Ce sont les résultats de ces travaux que nous résumons ici.

II. - Esquisse géographique (2)

La forme du Tibesti a été précisée par J. Tilho qui l'a

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(1) In M. Dalloni, *Mission au Tibesti*, Mém. Acad. Sc., t. 61, 1934.
(2) Le Tibesti, pays des Toubous, possède une terminologie géographique particulière: *Emi* = grande montagne; *Ehi* = montagne

représenté comme un massif triangulaire dont les arêtes principales, correspondant grossièrement aux formations volcaniques, forment un Y aplati.

La branche inférieure de l'Y, sensiblement SSE-NNW, est constituée par le grand édifice de l'Emi Koussi, point culminant du Tibesti et de toute l'Afrique saharienne (3.415 m). Relativement escarpé sur ses flancs Est, Sud et Ouest, il se prolonge par contre vers le Nord par la chaîne du Tarso Ahon, qui culmine également au-dessus de 3.000 m.

La branche droite de l'Y prolonge en réalité très directement vers le Nord-Est la chaîne Emi Koussi-Tarso Ahon. Bien que baptisée dans son ensemble Tarso Emi Chi par les Toubous, elle comporte une série de plateaux, notamment le Tarso Kozen et le Tarso Aozi. Au-dessus d'eux émergent des sommets déchiquetés dont le plus important est le Kégueur Tédi (3.150 m). Nous avons convenu d'appeler *Tibesti oriental* l'ensemble de ces premières unités géographiques.

La branche gauche de l'Y, orientée sensiblement Est-Ouest, est beaucoup plus importante que les deux autres. On peut y distinguer plusieurs groupes de massifs :

A l'Est, le *Tibesti central*, formé de hauts plateaux dont l'altitude varie entre 1.500 et 3.100 m (Tarsos Tiéroko, Toon, Yéga, Voon, Abéki). Il est séparé du Tibesti sud-oriental par la dépression du Miski, du Tibesti nord-oriental par celle du Yébbigué et d'un satellite plus septentrional (Tarso Ourari) par celle du Zoummeri.

Vers l'Ouest, la transition est plus ménagée vers le *Tibesti occidental*, essentiellement formé par les Tarsos Tamertiou, Dadoï, Toussidé, Timi et Tôh. Le point culminant se trouve à l'Emi Toussidé (3.265 m), qui domine le site célèbre du Trou au natron.

Nous décrirons les principaux édifices de chacune de ces régions, avant de dégager les conclusions d'ensemble valables pour la totalité des formations volcaniques.

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moyenne ou petite; *Tarso* = plateau (les grands volcans à caldeiras, de forme générale assez aplatie, sont aussi qualifiés de « tarsos »); *Enneri*, synonyme de l'arabe oued = vallée le plus souvent sèche.

III. - Les massifs volcaniques

A) Le Tibesti oriental.

1. - L'Emi Koussi (fig. 1 et pl. I à V).

Le massif de l'Emi Koussi est constitué par un cône bien individualisé et large de 60 à 80 km, qui domine directement les plaines désertiques du Borkou, sauf au Nord où, comme nous l'avons dit, une arête étroite et dentelée le relie à la chaîne du Tarso Ahon.

L'édifice volcanique repose sur un substratum de grès

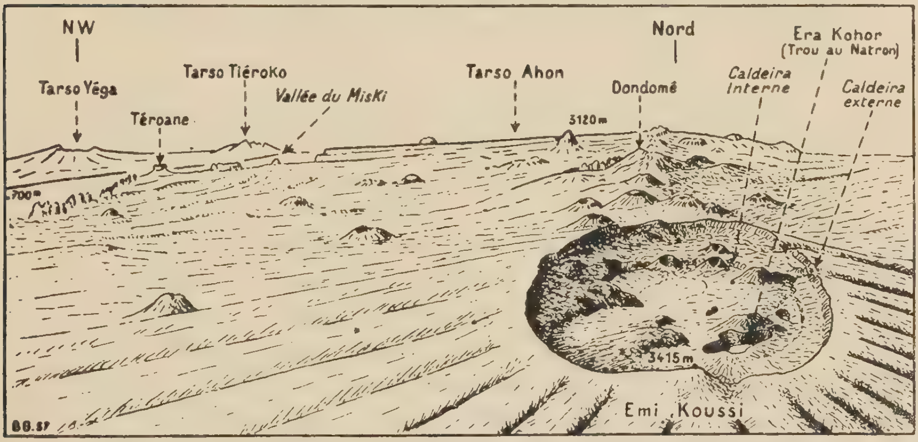

Fig. 1. - Vue cavalière de la région volcanique de l'Emi Koussi.

primaires et secondaires surélevé au-dessous de lui. Des failles NNW-SSE semblent donner au moins partiellement un caractère de horst à ce vaste bombement anticlinal ; mais quoi qu'il en soit de ce point de vue tectonique, la surface des terrains sédimentaires, comprise entre 500 et 1.000 m à la périphérie, doit atteindre près de 2.000 dans l'axe du massif.

Il est vraisemblable que le cône primitif s'est élevé aux environs de 4.000 m d'altitude. Cependant, à l'heure actuelle, le sommet est tronqué et remplacé par une caldeira ovale, de 12 à 15 km de diamètre, dont les remparts sont très bien conservés entre 3.000 et 3.415 m. Cette caldeira est, en fait, assez complexe et comporte :

— deux caldeiras d'effondrement, emboîtées l'une dans l'autre et profondes respectivement de 300 et 200 mètres;

— deux ou trois cratères d'explosion, localisés dans la caldeira d'effondrement interne; le plus grand de ces cratères, large de 2 à 3 km suivant ses axes, et profond de 350 m, est appelé « Trou au natron » du Koussi, ou « Era Kohor ».

Des puys basaltiques, aux formes souvent très fraîches, s'observent sur les bordures internes et à l'extérieur des caldeiras d'effondrement; la plupart des puys de bordure de la caldeira externe et des pentes périphériques paraissent plus anciens que ceux qui jalonnent la caldeira interne. Les cratères d'explosion sont certainement postérieurs aux premiers, mais sans doute antérieurs à quelques-uns des derniers.

Du point de vue pétrographique, l'ensemble de l'édifice débute, au-dessus du substratum, par une « série noire inférieure » qui n'est visible qu'en quelques points de la périphérie du massif et dans les ravins séparant du Tarso Ahon. Elle comprend essentiellement des andésites labradoriques passant aux basaltes, de structure porphyrique en général largement cristallisée et dont les éléments ferromagnésiens caractéristiques sont l'olivine et l'augite. Aucun appareil n'est visible dans cette série qui est peut-être d'origine fissurale.

La masse principale de l'Emi Koussi est constituée par des trachytes subalcalins, à structure microlithique porphyrique, avec phénocristaux d'augite aegyrinique et de hornblende brune, contenant parfois un peu de biotite secondaire. La composition moyenne de ces trachytes correspond aux paramètres de A. Lacroix I (II), 5, 2, 4.

Au sommet de cette « série blanche » (partie supérieure des remparts de la caldeira externe), les laves sont plus acides et tendent vers des rhyolites alcalines de paramètres I (II), (4) 5, 1, '4. Outre ces roches, on observe également des phonolites, soit en coulées interstratifiées dans la série (paroi du Trou au natron), soit en intrusion (caldeira interne), dont la composition moyenne correspond aux paramètres II, 6, 2, 4.

Les éruptions et épanchements d'une « série noire supérieure » ont eu lieu en plusieurs stades, que l'on peut diffé-

rencier notamment en basaltes des pentes (antérieurs au creusement des vallées actuelles, peut-être à mettre en rapport avec l'affaissement de la caldeira externe) et basaltes des vallées (comblant les vallées récentes, peut-être en rapport avec l'affaissement de la caldeira interne). Du point de vue pétrographique, toutes ces roches sont très proches les unes des autres et vont des basaltes andésiniques aux basanitoïdes.

Les explosions, probablement phréatiques, du Trou au natron et de ses satellites ont rejeté des cinérites à blocs qui ont largement saupoudré tout l'intérieur des caldeiras. A l'extérieur, les cinérites, probablement remaniées par les eaux, s'observent surtout au pied du volcan.

Ces cinérites ont sensiblement la même composition que les roches de la série blanche, mais contiennent des blocs de roches grenues parmi lesquelles nous avons déterminé une syénite néphélinique à aegyrine et biotite, de paramètres I', 6, 1, 4, ainsi qu'une diorite à augite et hypersthène, à la limite des gabbros, de paramètres II (III), 5, 4, 5. A. Lacroix a décrit, en outre, d'après des échantillons recueillis par J. Tilho, des syénites quartzifères à diopside, hornblende et biotite, de paramètres I (II), 5, (1) 2, 3 (4). Il faut noter que toutes ces roches correspondent aux formes grenues des laves des séries noire inférieure et blanche; comme aucune n'est connue dans le socle antécambrien, il est logique de supposer qu'il y a bien relation entre roches cristallisées et laves, les premières ayant été arrachées de leur gisement et rejetées à l'extérieur par les explosions qui ont formé les cratères.

Les seules manifestations actuelles du volcanisme de l'Emi Koussi sont représentées par les sources thermales de Yi-Yerra (38°), au pied Sud du volcan, vers 850 m d'altitude. Cependant, il existerait d'autres sources plus ou moins alignées sur une distance de 200 km vers le Sud et dont la température moyenne irait en décroissant jusqu'à celle d'Aïn Galakka, encore hypothermale (28°,2).

2. - Le Tarso Ahon.

Situé au NNW du Koussi, dans le prolongement surélevé de son soubassement, le Tarso Ahon (sensu lato) forme une chaîne longue de 100 km et large de 40 à 60 km. Du Sud au Nord, les principaux sommets sont le Dondomé (qui se raccorde au Koussi), l'Arken Ahon (3.120 m), le Tarso Ahon (sensu stricto, 3.325 m) et le Tarso Mohi (2.390 m).

Toute la dorsale de ce massif est occupée par de larges épanchements de basaltes très fluides, aussi, de loin, a-t-on l'impression de voir un plateau horizontal, alors qu'en réalité les versants sont très abrupts, tant à l'Est qu'à l'Ouest et que les pitons rhyolitiques ou trachytiques non ennoyés sous les basaltes se montrent très déchiquetés et d'accès difficile.

Du point de vue pétrographique, on retrouve sensiblement les mêmes constituants que dans le massif du Koussi:

A la base, une série noire inférieure, dont le sommet est du reste fréquemment interstratifié dans la série blanche, en formant alors une série noire intermédiaire (disposition bien observée dans le versant Est, au Sud de Goumeur). Les roches sont des basaltes et andésites en général assez bien cristallisés, à olivine et augite, souvent riches en zéolithes. Des niveaux de cinérites rouges ou noires peuvent être conservés entre les coulées.

Au-dessus, une série blanche qui forme la masse principale des édifices majeurs et les principaux sommets. Il semble qu'il s'agisse de roches en général plus alcalines qu'au Koussi (rhyolites, rhyolitoïdes ou trachytes alcalins ou hyperalcalins). Les termes extrêmes sont représentés dans le Tarso Mohi par des rhyolites hyperalcalines (comendites) de paramètres I, 4', 1, 3' et par des trachytes quartzifères sub-alcalins, à pyroxène et amphibole, de paramètres I', '5, 2, 4. Notons également un trachy-phonolite à aegyrine et hornblende brune, de paramètres I', 5, 1 (2), '4, en intrusion dans les grès à l'Ouest du massif (Enneri Kichimerer).

Enfin, une série noire supérieure, débutant par des basaltes des plateaux largement suspendus au-dessus des vallées actuelles, puis des basaltes récents dont les émissaires sont

bien conservés, avec des coulées descendant très loin dans les vallées latérales. Comme au Koussi, ces basaltes sont très proches les uns des autres (basaltes mélanocrates passant à des basanitoïdes).

L'histoire du Tarso Ahon se distingue seulement de celle du Koussi par l'absence de formation de caldeiras, ainsi que par l'absence de manifestations actuelles. Le fait marquant qui caractérise la phase récente de ce volcanisme est l'alignement des puys basaltiques dans l'axe même de la montagne, prolongement de celui du Koussi. Il semblerait indiquer que les basaltes tardifs ont profité d'un rejeu des failles, dans la zone de surélévation maxima du substratum.

3. - Le Tarso Emi Chi.

Au Nord de l'unité du Tarso Ahon, mais en liaison étroite avec lui, le Tarso Emi Chi se présente sous forme d'un rectangle de 100 et 70 km de côtés, allongé du SSW au NNE. Ses versants Nord et Est sont abrupts (le sommet du Kégueur Tédi culmine à 3.150 m dans le NE), alors qu'il s'abaisse en pente relativement douce vers le Sud et l'Ouest. Le substratum antévolcanique s'abaisse également de l'Est vers l'Ouest (1.700 m à Kouaceur et au Kré Dahon, 900 m seulement à Omchi).

Les meilleures coupes sont fournies par les versants Est et Sud. Elles montrent sensiblement la même succession que celle du Tarso Ahon.

La série noire inférieure et la série noire intermédiaire (en intercalation dans la série blanche) sont également basalto-andésitiques. Bien que de nombreux niveaux de cendres soient interstratifiés dans les coulées, nous n'avons toujours pas observé d'appareils conservés et l'origine fissurale demeure la plus probable.

La série blanche forme la masse principale des massifs importants de l'Emi Chi (Kégueur Tédi, Mouskorbé, Tarso Adar, Tarso Chididemi, aiguilles de Kozen et de Chebedo sur le versant Est; Tarso Toudougou au Sud; Tarsos Goziydi, Kazena Lulli, Boubou, Godoon au centre).

Comme dans le Tarso Ahon, et plus encore, ces venues sont nettement plus alcalines que celles du Koussi. Dans la partie inférieure de la série blanche (au-dessous de la série noire intermédiaire), les trachytes alcalins et hyperalcalins dominent, bien que les rhyolites soient assez fréquents. Au Nord du massif, de nombreux dykes de microsyénites hyperalcalines (sölvsbergites) traversent les grès de Nubie et la série noire inférieure suivant une direction NW-SE très régulière, qui est celle des failles affectant les grès primaires à l'Est du massif et une partie des failles recoupant les grès de Nubie au Nord. La partie supérieure de la série blanche est essentiellement composée de rhyolites ou rhyolitoïdes alcalines ou hyperalcalines. Les éléments ferro-magnésiens les plus fréquents sont la riebeckite et, plus rarement, l'aegyrine, la lanéite et la cossyrite. Les faciès subalcalins du Tibesti sud-oriental sont ici très rares et nous n'avons pas observé de phonolites.

Dans l'ensemble de la série blanche, les coulées se localisent au voisinage des centres d'émission. En dehors de ceux-ci, on ne trouve que des produits de projection, cinérites et surtout ignimbrites. Cependant, il n'existe aucune caldeira importante, mais néanmoins, en plusieurs points, le relèvement des séries noires inférieures par l'intrusion des séries claires est bien visible: c'est le cas en particulier à la périphérie des aiguilles de Chebedo et de celles du Tarso Kazena-Lulli.

La série noire supérieure débute, comme toujours, par des tables basaltiques suspendues au-dessus du réseau hydrographique actuel et issues de puys en général très démantelés (Tarsos Mouroui, Barkazenti, Tobou, Kazena-Lulli, Adar). Ensuite ont apparu une quantité de petits puys qui s'alignent suivant des directions NW-SE comme les dykes de microsyénites précédemment cités et, sans doute, pour les même raisons tectoniques. Les deux principaux alignements se trouvent sur les axes Goumeur-Yebbi Bou et Torros-Boubou. A partir de ces puys ont été émises des quantités de laves considérables. Sur les tarsos mêmes, les coulées sont très étendues

mais habituellement peu épaisses, tandis que, dans les vallées, le surcreusement des enneris actuels (dans le Yébbigué par exemple) permet de les observer parfois sur de grandes épaisseurs.

Du point de vue pétrographique, la série noire supérieure est assez homogène dans son ensemble. Il s'agit toujours de basaltes labradoriques à olivine et augite, en général très vitreux et scoriacés à la surface des coulées, beaucoup plus cristallins en profondeur.

Aucune manifestation volcanique actuelle n'est connue dans le Tibesti nord-oriental.

B) Le Tibesti central.

C'est assez conventionnellement que nous faisons commencer une unité différente à l'Ouest de l'alignement Sud-Nord des vallées du Miski et du Yebbigué (qui correspond grossièrement au 18e méridien) et que nous la faisons se poursuivre jusqu'à l'étranglement des formations volcaniques entre Zouar et Bardaï, un peu à l'Ouest du 17e meridien. Tel quel, le Tibesti central, ensemble de hauts plateaux, large de 120 km dans tous les sens, présente cependant un certain nombre de caractères particuliers qui motivent sa distinction à tous égards. Son point culminant paraît être à l'Ehi Mousgou (3.100 m), dans l'Ouest du massif.

1. - Le Tarso Ourari.

On désigne sous ce nom la partie la plus septentrionale du Tibesti central, au Nord de la dépression du Zoummeri. Elle forme une bande orientée WNW-ESE, longue d'environ 60 km et large de 20 à 30 km. On y trouve surtout d'épaisses coulées noires anciennes, sans coulées claires interstratifiées, mais percées d'extrusions acides en aiguilles ou en dômes. Au delà de l'avancée extrême des basaltes vers le Nord, ces extrusions peuvent sortir directement des grès de Nubie. Enfin, quelques tables de basalte des plateaux semblent clôturer l'histoire volcanologique de cette région.

Les séries basaltiques anciennes sont constituées par une succession de coulées de basaltes souvent doléritiques, à olivine et pyroxène. D'assez nombreux filons de même nature les recoupent et paraissent constituer les origines des coulées supérieures.

Vers le SE, ces basaltes se relient à ceux du Tarso Toon où la série blanche est bien représentée, ce qui permet de distinguer la série noire inférieure et la série noire intermédiaire. Mais ici, la série blanche n'est plus représentée que par quelques niveaux de ponces fines flottées, interstratifiées avec des cinérites fines et des diatomites blanches, ce qui indique la présence d'un épisode lacustre entre deux épisodes basaltiques dont le plus récent (série noire intermédiaire) est nettement le plus important.

Les extrusions claires varient depuis des rhyolites alcalines leucocrates (Ehi Owarda), des trachytes quartzifères hyperalcalins (dôme de la piste Bardaï-Kilébégué), des trachytes à fayalite, aegyrine et riébeckite (dôme Sud de l'Abéchérade), jusqu'à des phonolites à sodalite et aegyrine (pic de la balise et structure annulaire du Tirenno).

Plusieurs de ces extrusions présentent une structure annulaire apparente, soit complète (piste Bardaï-Kilébégué), soit incomplète (Tirenno). Il est d'ailleurs possible que l'impression de structure annulaire soit donnée dans certains cas par le redressement des coulées antérieures sous la poussée des extrusions. Par exemple, la structure de la piste Bardaï-Kilébégué correspond à un dôme central de trachyte quartzifère hyperalcalin (de 900 m sur 500 m), entouré d'un anneau de dolérite à olivine et augite qui peut être une coulée de lave noire inférieure plutôt qu'une intrusion distincte.

Les basaltes de plateau se distinguent des basaltes anciens qu'ils ennoient par la présence de points de sortie bien conservés (neck du Goudresso ou Wobou, et neck du Toukoundjiou par exemple) ainsi que par la prismation régulière de leurs coulées.

La surface irrégulière d'ennoyage des basaltes anciens par les basaltes de plateau indique une phase d'érosion entre

les deux émissions. Cependant leur situation largement suspendue aux-dessus des vallées actuelles permet de les distinguer facilement des basaltes récents de vallée, qui n'existent pas ici.

2. - La structure radiaire de Kilébégué.

Au SE du Tarso Ourari, à sa jonction avec le Nord du Tibesti oriental, en rive droite de la vallée du Yebbigué au Nord de Kilébégué, apparaît un paysage volcanique d'une grande complexité. Sur une surface de 10 km sur 7 km, une centaine de dykes et filons de trachyte divergent d'un point situé vers le tiers Sud et matérialisé par quelques aiguilles. En fait, la majorité des dykes sont groupés suivant deux faisceaux de directions privilégiées SSW-NNE et WNW-ESE.

Dans le Yebbigué, on voit ces dykes traverser la série noire inférieure, tandis qu'à l'Est ils sont recouverts par des coulées de la série noire intermédiaire. Leur âge relatif est donc bien précisé et équivalent de celui des dykes de sölvsbergite de direction NW-SE traversant la série noire inférieure au Nord du Tibesti oriental.

Au point de vue pétrographique, il y a également une grande ressemblance entre ces dykes divers. Il s'agit de trachytes sodiques quartzifères, souvent très cristallins, passant à des microsyénites alcalines (sölvsbergites). Les éléments ferromagnésiens dominants sont la riébeckite ou une amphibole voisine et plus rarement la cossyrite. Le quartz n'est pas toujours présent.

Pour expliquer cette structure, constatons tout d'abord que les directions dominantes des faisceaux de dykes correspondent aux directions des failles affectant les grès de Nubie visibles à l'aval (Omchi). Une intrusion massive d'un magma trachytique peut avoir réouvert un certain nombre de ces failles formant zones de moindre résistance et provoqué des cassures dans la série noire inférieure. Le long de ces cassures se seraient injectés les dykes de microsyénites, alors que dans l'axe de l'intrusion le magma se matérialisait par les aiguilles. Un effondrement de la partie centrale pos-

térieur aux épanchements, se traduisant en bordure par quelques failles concentriques, explique l'absence de bombement dans l'axe de l'intrusion.

Cette hypothèse semble confirmée par l'observation sur photos aériennes, d'une structure analogue quoique de plus petite taille au Nord d'Ouri (NE du Tibesti oriental), montrant les grès primaires soulevés par une intrusion phonolitique autour de laquelle s'irradient de nombreux dykes de phonolite observés sur le terrain; les structures annulaires du Tarso Ourari et les autres types de structures en dômes volcano-tectoniques que nous allons voir plaident dans le même sens.

3. - Le Tarso Tiéroko (pl. VI, 2).

Au Sud de la structure de Kilébégué, au SW de Yebbi-Bou, existent aussi deux intrusions notables de trachytes ou rhyolites, qui traversent les séries noires inférieure et moyenne, mais nous les avons seulement décelées sur photographies aériennes et ne les décrivons donc pas.

Par contre, à leur suite selon un alignement SSW-NNE, nous avons étudié le Tarso Tiéroko, à la limite du Tibesti central, devant le Tarso Mohi (Tibesti oriental). Il s'agit d'un cône important, de 30 km à la base, dont le sommet affaissé a fait place à une caldeira large de 8 km environ. Ses remparts, contrairement à ceux de la caldeira du Koussi, sont fort attaqués par l'érosion et dessinent des sommets déchiquetés visibles de très loin (2.910 m). Il sont constitués seulement par la série noire inférieure qui repose sur un substratum de schistes antécambriens. La série blanche n'affleure qu'à l'intérieur de la caldeira et dans deux petites sorties latérales. Aucune série plus récente ne semble exister.

Du point de vue pétrographique, la série noire inférieure débute par des brèches basaltiques à gros blocs, associées à des cinérites; puis viennent de puissantes coulées basalto-andésitiques. Ces dernières varient depuis des basaltes labradoriques β, de paramètres III, 5, 4, (4) 5, jusqu'à des dacitoïdes andésiniques α, à hypersthène, de paramètres 'II, 4 (5),

3, 4, avec toute une série de termes intermédiaires andésitiques.

La série blanche est constituée essentiellement par des rhyolites leucocrates dellénitiques, de paramètres I, (3) 4, 2, '4. A l'extérieur de la caldeira existent seulement des produits de projection de même composition (cinérites et surtout ignimbrites).

La caldeira du Tiéroko ne semble pas due à un effondrement important. Il semble au contraire qu'il y ait eu d'abord soulèvement des séries noires anciennes au moment de l'intrusion rhyolitique, car leur plongement périphérique paraît dépasser des valeurs normales pour des coulées (30°). Après seulement, aurait eu lieu un affaissement limité, avec formation de la caldeira et rejet des cinérites et ignimbrites.

4. - Le Tarso Toon (fig. 2 et pl. VIII, 1).

Situé à 40 km au NNW du Tiéroko, le Tarso Toon est un volcan dont la base mesure 25 à 30 km et dont le sommet est également remplacé par une caldeira de 9 à 12 km de diamètres. Les remparts, assez irréguliers, atteignent l'altitude de 2.625 m.

Il semble que l'on puisse distinguer à la base, comme représentant la série noire inférieure, des laves et des brèches basaltiques à blocs et lentilles interstratifiées de galets basaltiques analogues à celles du Tiéroko. Puis viennent des trachytes, peu développés dans l'Ouest, mais qui affleurent plus largement dans l'Est (Enneri Yeski) où ils passent à de grandes masses d'ignimbrites.

Ensuite, l'essentiel des flancs du volcan est formé par une puissante accumulation de minces coulées représentant sans doute les basaltes de la série noire intermédiaire; vers l'Ouest, ils disparaissent sous les cinérites et ignimbrites récentes, issues du volcan du Tarso Voon. Enfin, la caldeira est entièrement occupée par des extrusions et ignimbrites rhyolitiques qui traversent aussi les basaltes et trachytes, en filons parallèles aux génératrices du cône ou au rebord du cratère. Des analyses effectuées sur des échantillons de la mission

Dalloni montrent qu'il s'agit de rhyolites dellénitiques analogues à celles du Tiéroko.

Comme dans ce dernier volcan, il est probable qu'après les éruptions et épanchements des séries inférieures, l'intrusion des rhyolites a provoqué un soulèvement de ces séries beau-

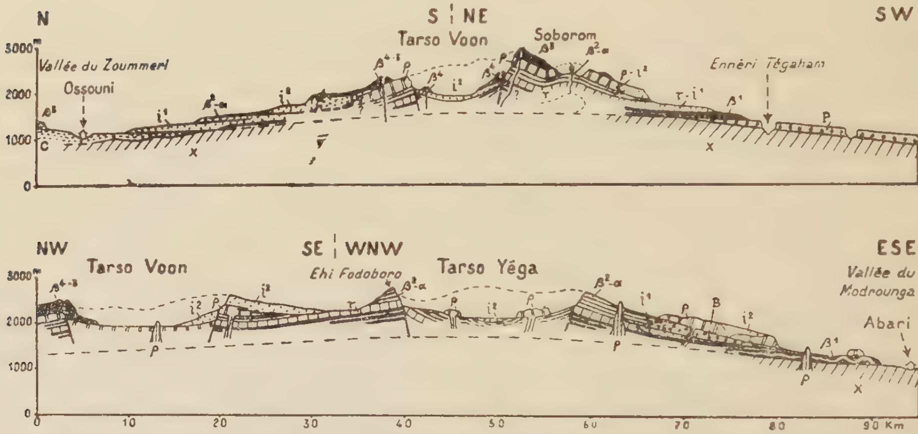

Fig. 2. - Coupes schématiques des volcans du Tarso Voon et du Tarso Yéga. i = ignimbrites (anciennes 1, récentes 2); B = brèche péléenne; β = basaltes (inférieurs 1, intermédiaires 2, des plateaux 3, récents 4); α = andésites; τ = trachytes; ρ = rhyolites; C = Crétacé; P = Primaire; X = Antécambrien.

coup plus important que les tassements ou refusions qui ont donné naissance à la caldeira.

5. - Le Tarso Yéga (fig. 2 et pl. VI, 1).

A partir du Tarso Toon, suivant un alignement grossier en direction SSW, se rencontrent plusieurs petits édifices, dont l'Ehi Yey que nous n'avons pas étudié, puis, à 50 km, le très grand volcan du Tarso Yéga, large d'environ 50 à 70 km à la base. Strictement, ce nom est réservé par les Toubous à une caldeira géante, dont les diamètres varient entre 17 et 20 km, avec des altitudes allant de 2.150 m au centre jusqu'à 2.400 et 2.800 m pour le haut des remparts (Ehi Fodoboro).

Les flancs du volcan sont dissymétriques et s'étendent davantage vers l'Est et le SE que vers le Sud et le SW; au Nord et au NW, ils sont recouverts par les cinérites et ignimbrites récentes du Tarso Voon. La succession des laves est sensiblement la même que celle qui a été définie dans le Tibesti oriental:

Au-dessus des schistes antécambriens et grès primaires (qui s'élèvent de 1.100 m dans l'Est jusqu'à 1.800 m environ sous la caldeira), vient la série noire inférieure. Dans l'Enneri Lelleby, affluent de rive droite du Modrounga, on y distingue à la base de grosses coulées prismées et des masses considérables de produits de projection, puis une brèche à gros blocs due probablement à des dépôts de nuées ardentes de type péléen, associée à des cinérites à blocs et à des cinérites stratifiées, plus fines. Le sommet de la série paraît essentiellement constitué par des coulées à pendages faibles et réguliers vers l'extérieur du volcan.

La partie inférieure de la série blanche a été mal observée sur le terrain car elle ne se développe que vers le NE et dans la base du Fodoboro à l'Ouest. De nombreux filons de roches claires recoupent la série noire inférieure, mais il est difficile de distinguer s'ils alimentent cette partie inférieure ou la partie supérieure de la série blanche.

La série noire intermédiaire forme l'essentiel des remparts de la caldeira là où ils sont bien conservés (moitié orientale et Fodoboro dans l'Ouest) et tout le haut des pentes extérieures dans ces mêmes régions. Il s'agit d'une succession régulière de coulées basaltiques ou andésitiques, d'abord massives, puis porphyriques et fortement bulleuses, parfois même scoriacées et rubéfiées à leur surface; leur épaisseur, dans le Fodoboro, peut être estimée à 400 mètres.

La partie supérieure de la série blanche est représentée à l'intérieur de la caldeira par quatre masses principales, hautes de 100 à 400 mètres. Ce sont des rhyolites leucocrates ou rhyolitoïdes sodiques, à plagioclases exprimés qui offrent toutes un débit en pelure d'oignon, très analogue à celui observé pour les rhyolites hyperalcalines du Tarso Goziydi.

A l'extérieur de la caldeira, 3 autres sorties claires forment l'Ehi Tionna et l'Ehi Sunni au NW, l'Ehi Yodeï au Sud. Cette dernière intrusion semble avoir soulevé les coulées plus anciennes car, à son voisinage, elles montrent des pendages différents de ceux qu'elles devraient avoir en venant du centre du Tarso Yéga.

La série noire supérieure des plateaux est limitée à quelques coulées à l'extérieur du volcan (Tarso Koré au NE) et dans l'intérieur de la caldeira. Ces basaltes recouvrent indifféremment les séries antérieures érodées et sont eux-mêmes très disséqués par l'érosion. Il n'y a pas ici de manifestation volcanique plus récente.

6. - Le Tarso Voon et l'Ehi Mousgou (fig. 2 et pl. VII à IX).

Ici encore, les indigènes appliquent strictement la dénomination de Tarso Voon à l'intérieur d'une grande caldeira, située 30 km au NW de celle du Tarso Yéga. Nous étendons ce terme à l'ensemble du volcan, l'un des plus remarquables du Tibesti central.

Ses limites extérieures (40 à 60 km de diamètres) sont difficiles à définir car le raccord avec les édifices voisins est souvent étroit. Par contre la caldeira est fort bien circonscrite, avec des axes de 14 et 18 km entre des remparts culminant vers 2.000 à 2.900 m d'altitude. Le fond, relativement plan à l'altitude de 1.900 m et sur un diamètre moyen de 9 km, est limité par les couches de l'ancien volcan très nettement affaissées vers l'intérieur, cet affaissement pouvant être estimé à un millier de mètres.

En groupant les observations faites à la périphérie du volcan et celles résultant de l'examen des remparts de la caldeira, il est possible de retrouver la succession complète des séries déjà définies dans le Tibesti oriental. La série noire inférieure semble n'affleurer qu'à la limite SW, au-dessus des schistes antécambriens et grès primaires, comme au Tarso Yéga. Au-dessus, viennent les trachytes de la base de la série blanche, les andésites et basaltes de la série noire intermé-

diaire, les rhyolites du haut de la série blanche. Leur composition est tout-à-fait analogue à leurs homologues du Tarso Yéga, sauf pour la série blanche supérieure où l'on note l'association des rhyolites leucocrates avec des rhyolites hyperalcalines.

Vers le Sud et l'Est de la caldeira, ces diverses séries se tranchent obliquement: il semble y avoir eu là plusieurs points de sorties, notamment pour les rhyolites. Des aiguilles rocheuses traversant les trachytes et andésites paraissent correspondre ainsi à des cheminées antérieures à la formation de la caldeira.

Dans le versant Nord du volcan, la coupe de l'Enneri Mousgou montre que les coulées à rattacher à la série noire intermédiaire sont séparées par des horizons de diatomites, jaspes et cinérites à blocs. Elles surmontent des ignimbrites qui passent sans doute aux trachytes inférieurs, mais elles sont surtout recouvertes par une nouvelle et énorme masse d'ignimbrites rhyolitiques (puissance dépassant 300 m). Ces ignimbrites supérieures revêtent d'ailleurs tout le paysage jusqu'à des distances de 15 à 35 km autour de la caldeira. Elles sont aussi conservées sur quelques unes des pentes intérieures de cette caldeira du Tarso Voon et vont également contribuer au remplissage de celle du Tarso Yéga qui n'en avait pas émis d'aussi récentes. Elles rappellent celles de l'Emi Koussi, mais avec un développement beaucoup plus considérable.

Cette formation est cependant recouverte, surtout vers le NW, par les basaltes de la série noire supérieure. Il s'agit de coulées, habituellement peu épaisses mais pouvant être fort longues, qui sont issues soit de petits puys jalonnant la zone de fractures en bordure de la caldeira, soit de volcans plus importants, notamment l'Ehi Mousgou (3.100 m), au coeur duquel transparaissent d'ailleurs des sorties blanches plus anciennes. Ces basaltes sont labradoriques, à olivine et augite, et fort semblables à ceux du Tibesti oriental.

7. - Le dôme volcano-tectonique de Soborom (fig. 2 et pl. X à XII).

Cinq kilomètres environ à l'Ouest de la caldeira du Tarso Voon, en tête de l'Enneri Tégaham, se trouve le site remarquable des sources de Soborom. Elles se localisent au coeur d'un petit dôme, dans la série noire intermédiaire, les rhyolites et les basaltes supérieurs plongeant de part et d'autre, non sans nombreuses failles et accidents secondaires.

Sur une distance de près de 500 m, entre 2.400 et 2.300 m d'altitude environ, les roches sont transformées et colorées par des fumerolles et recouvertes par des incrustations de chlorure de fer, de chlorure d'ammonium, de gypse et de sulfates variés, ainsi que de soufre. Un groupe supérieur comprend la « Source tonnante », grande marmite bouillonnante d'eau boueuse à 70° avec forte odeur de SO_2, puis un soufflard à 90°; un groupe central renferme une dizaine de sources et « volcans » de boues sulfureuses avec des températures de 56 à 82°, ainsi que deux soufflards dont l'un, très violent, rejette de la vapeur à 100°; un groupe oriental prolonge le précédent avec des sources de 62 à 85° et deux soufflards à 80 et 90°; enfin vers le Sud, une seule source à 38° sort d'un bassin utilisé par les indigènes pour soigner leurs douleurs et maladies de peau. Toutes ces eaux sont acides (acide sulfurique libre) et les boues sont faiblement radioactives.

Il est vraisemblable que la structure en dôme de cette région est due à l'injection très récente (postérieurement aux basaltes des pentes) d'un petit laccolite situé à faible profondeur et qui ne serait pas encore totalement consolidé; d'où l'activité intense des fumerolles, solfatares et sources thermales, la plus remarquable de tout le Tibesti.

8. - Le Tarso Abeki.

Le Tarso Abeki est un grand édifice complexe situé 40 km au Sud de Bardaï, à la limite entre le Tibesti central et le Tibesti occidental. Suivant un axe Nord-Sud, son diamètre

est d'une quarantaine de kilomètres, mais ses flancs orientaux sont recouverts par les ignimbrites supérieures du Tarso Voon ou les basaltes récents du Mousgou et de Soborom, tandis que ses flancs occidentaux se relient aux laves du Tarso Tamertiou ou sont recouverts par les ignimbrites du Tarso Toussidé.

C'est donc au Nord et au Sud seulement que l'on observe les coulées les plus anciennes (basaltes de la série noire inférieure dominant l'Est de l'Enneri Oudingueur notamment). Au-dessus viennent la série blanche inférieure, puis les basaltes et andésites de la série noire intermédiaire. La série claire supérieure n'apparaît guère que sous la forme d'une quantité de pitons et de dykes qui occupent la totalité de ce qui a pu être une caldeira centrale, mais qui est actuellement une forme en relief et non en creux (altitudes de 2.600 à 2.728 m).

Large de 10 à 12 km, cette aire d'intrusions a certainement contribué au soulèvement des formations qui l'entourent. En effet, entre le cœur rhyolitique et les laves périphériques existe une couronne presque complète de schistes antécambriens (avec quelques grès primaires), large de 1.500 à 3.000 m et portée à une altitude de 2.200 à 2.300 mètres. Sans doute, se trouve-t-on en ce point sur un axe de soulèvement du socle antévolcanique (axe WNW-ESE Abo-Aguer Taï), mais l'exaltation a été localement accrue par l'intrusion qui fournit ainsi un exemple de dôme volcano-tectonique plus grandiose que tous ceux reconnus plus à l'Est.

Aucune formation volcanique récente n'est connue au Tarso Abeki.

C) Le Tibesti occidental.

Le Tibesti occidental prolonge le Tibesti central au delà du Tarso Abeki par la zone du Tarso Tamertiou. Puis vient un vaste plateau couvert de produits de projections et appelé Tarso Toussidé; il est dominé par les grands cônes de l'Emi Toussidé (3.265 m) et de l'Emi Ti ou Timi (3.040 m), ainsi que par les massifs plus modestes du Sosso, des Dadoï, du Botoum et du Tatodomji; il est enfin creusé par la grande

caldeira du Pré-Toussidé et par les cratères d'explosion du Doon (« Trou au natron ») et du Doon Kidimi.

Au NW du Tarso Toussidé, une série de puys et de coulées basaltiques récents forment le Tarso Tôh, qui termine dans cette direction l'ensemble volcanique tibestien.

1. - Le Tarso Tamertiou.

Au sens large, le Tarso Tamertiou est un massif complexe constitué surtout par un empilement de coulées provenant

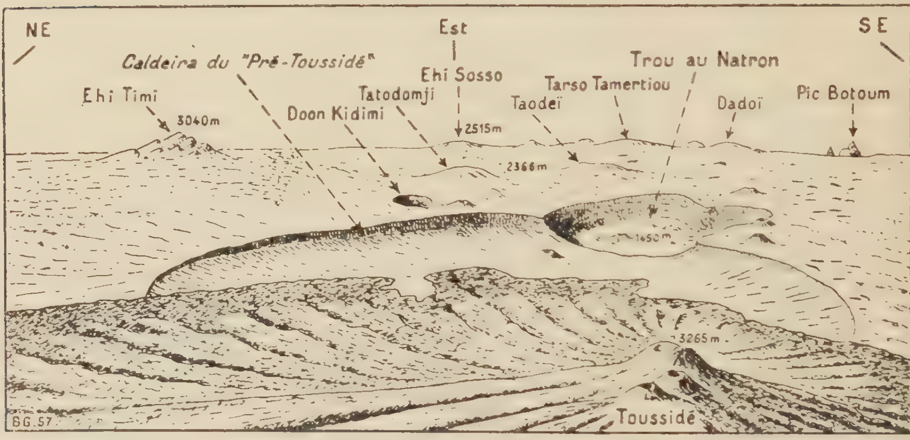

Fig. 3. - Vue cavalière de la région volcanique du Toussidé.

soit du Tarso Abeki au NE, soit du Dadoï au SW. Il comprend le Tamertiou proprement dit au NW, l'Ehi Doma au SW et le Tarso Tougoussi à l'Est.

On y retrouve la succession de laves habituelles: la série noire inférieure, essentiellement basaltique, est surtout bien représentée à l'Est. La série blanche inférieure, également bien développée dans l'Est où elle semble constituer la terminaison occidentale du Tarso Voon avec une puissance dépassant 300 m. Elle débute soit par un agglomérat à ciment de verre noir (à l'Est), soit par des cinérites et ignimbrites (au SE). Les coulées qui les surmontent sont finement porphyriques, sans quartz visible, probablement trachytiques. La série noire intermédiaire, plus épaisse que l'inférieure, est

mieux développée à l'Ouest où elle forme l'essentiel du Tarso Tamertiou sensu stricto; elle est composée de roches à faciès andésitique et à zéolites. La série claire supérieure est généralement constituée par de puissantes coulées prismées, 4 ou 5 dans une falaise de 300 m, et traversées par des filons épais semblant avoir alimenté les coulées supérieures. Quelques grosses masses extrusives prismées s'observent localement sur toute la hauteur en bordure de la falaise. Cette série forme, outre la partie supérieure de l'Ehi Atigoroumki (flanc W du Tarso Abeki), de grandes tables limitées par des falaises rectilignes, hautes de plusieurs centaines de mètres, qui témoignent d'une érosion intense depuis leur émission. Des cinérites et ignimbrites récentes, issues du Tarso Toussidé, ennoient toutes les vallées et sont largement recreusées par les enneris actuels.

2. - Le Tarso Toussidé.

Le plateau volcanique du Toussidé, qui s'étend sur une surface d'environ 6.000 km^2, recouvre au SE des schistes antécambriens, au SW et au NW des grès primaires, au NE des grès de Nubie. Ce substratum dépasse 2.000 m d'altitude au SE (près du Botoum), mais il s'abaisse au Nord (1.400 m dans l'Enneri Oudingueur) et surtout au NW (1.000 m à l'Est de Wour).

Tout le plateau est revêtu d'un manteau de cinérites récentes qui masquent presque toutes les formations antérieures. Ainsi, les séries noires anciennes n'ont pu être observées qu'à l'Ouest de l'Enneri Oudingueur où elles forment des tables basaltiques prolongeant celles du Tarso Abeki. Cependant les séries blanches sont bien connues grâce aux massifs qui émergent des cinérites récentes, ainsi que par les remparts de la caldeira du « Pré-Toussidé » et des cratères d'explosion voisins. Quant aux formations récentes autres que les cinérites, elles sont représentées par de petits puys basaltiques dispersés à la surface du plateau et surtout par les énormes volcans du Toussidé et du Timi.

3. - Les massifs appartenant à la série blanche.

Au NW du Tarso Tamertiou, le premier massif saillant hors du Tarso Toussidé est l'Ehi Sosso qui culmine à 2.515 m et présente un diamètre de 4 à 5 km. Les laves qui le constituent (rhyolites leucocrates) offrent un débit en pelure d'oignon analogue à celui des massifs centraux du Tarso Yéga.

Neuf kilomètres vers l'Ouest, le Tatodomji est un massif peu élevé et grossièrement circulaire (1.500 m de diamètre environ) également constitué de rhyolites leucocrates porphyriques à structure sphérolitique. Cette sortie est peut-être responsable des anomalies observées en contre-bas, dans la falaise du cratère d'explosion du « Trou au natron », distant seulement de 1 km vers le SW.

Le Grand Dadoï, immédiatement au SW du Tamertiou, correspond à un groupe de trois grands massifs séparés par d'étroites dépressions comblées de cinérites récentes, de 13 km de long sur 5 à 7 de large. Plus à l'Ouest, le Petit Dadoï est une colline de 3 km de long qui est surmontée par un petit cône basaltique. Ces diverses sorties, trachytiques (ou rhyolitiques ?) peuvent avoir fourni une partie des coulées claires du Tarso Tamertiou et du Trou au natron.

Le Botoum et le Botoudoma (ou Petit Botoum) sont des extrusions rhyolitiques situées 10 km au Sud du Trou au natron. Le Petit Botoum est une aiguille simple, à prismation verticale; le Grand Botoum présente aussi une prismation verticale dans sa partie supérieure, mais sa base a la forme d'un dôme. A l'Ouest, et provenant de toute évidence du Botoum, une épaisse coulée à pendage Ouest s'étale sur les grès. Elle est séparée du Botoum même par une zone déblayée où affleurent les schistes antécambriens et qui correspond sans doute à l'ancien emplacement des produits plus tendres, scories et lapilli, formant l'ancien cône. Vers l'Est, quelques filons traversent les schistes et font partie du même ensemble. Ce sont des rhyolites fluidales, à aegyrine et riébeckite, con-

tenant des enclaves de granite à aegyrine et riébeckite de même composition que la lave.

4. - La caldeira du «Pré-Toussidé».

Nous avons appelé ainsi la grande dépression, large de 13 à 14 km, qui est située au milieu du Tarso, immédiatement à l'Est du Toussidé, et qui est remplie actuellement aux trois quarts par les laves issues de ce volcan. Au dessous d'elles se trouvent aussi conservées des cinérites à blocs rejetées par les deux cratères d'explosion voisins. Les remparts demeurent néanmoins bien visibles sur les deux tiers de leur extension primitive, avec des hauteurs dépassant 200 m à l'Est et s'abaissant à 50 m au SW.

Les roches constituant ces remparts sont les mêmes que celles qui forment les parois des cratères d'explosions, où leur succession peut être mieux étudiée. Il faut cependant noter en plus, vers le Sud, la présence d'une andésite porphyrique à olivine et augite, tout à fait aberrante dans cette série.

Il est vraisemblable que cette caldeira résulte de l'affaissement du sommet d'un ancien grand volcan rhyolitique ayant fourni la majorité des coulées de la région. Les cinérites et ignimbrites supérieures auraient été rejetées pendant cet affaissement, à l'exception des produits, plus récents encore, qui résultent de l'explosion des cratères voisins.

5. - Le «Trou au natron», ou Doon.

Ce site, le plus célèbre du Tibesti, est un gigantesque cratère d'explosion, large de 6 à 8 km, limité par des parois subverticales de 700 m au Sud et près de 1.000 m au NE. Une partie du fond de la dépression est couverte par des dépôts de carbonate de soude (trona) d'une blancheur éclatante, sur laquelle tranchent en sombre quatre petits édifices volcaniques.

Dans la paroi Sud, par laquelle s'effectue la descente, on observe un empilement régulier de coulées de laves à débit prismé, que recouvrent, sur les 100 m supérieurs, des cinérites et ignimbrites. Les autres faces montrent une moins

grande régularité et les couches s'entrecroisent avec des pendages non négligeables, notamment vers le NE, à l'aplomb du Tatodomji où les plongements sont NW. Des filons verticaux ou obliques recoupent les couches inférieures et semblent avoir alimenté des coulées à mi-pente. On remarque, en outre, des dépôts lacustres à Gastéropodes et des diatomites, qui sont conservées à un niveau supérieur au fond actuel.

Du point de vue pétrographique, les coulées sont constituées en majorité par des rhyolites ou rhyolitoïdes hyperalcalines, à riébeckite, aegyrine et parfois fayalite. Vers la base, il est possible qu'il existe également des trachytes. Quelques passées de laves noires à faciès d'obsidiennes sont peut-être des pantellérites.

Le plateau, à l'extérieur du Trou, et un redan au SW sont recouverts de cinérites rejetées par l'explosion principale, qui contiennent, outre des blocs de roches du socle et des laves variées, des blocs parfois énormes d'une roche très particulière, qualifiée de « rhombenporphyr » par A. Lacroix. Il s'agit d'une microsyénite à phénocristaux d'anorthose aplatie et de section rhombique, dont les éléments ferromagnésiens sont la fayalite, l'augite et parfois l'aegyrine; ses paramètres sont I (II), '5, '2, '4, donc très voisins de ceux des doréites que nous avons trouvées au volcan actuel du Toussidé, immédiatement dans l'Ouest.

Sur le rebord du cratère, de petits puys basaltiques sont intersectés partiellement par l'explosion et recouverts par les cinérites à blocs.

Quant aux autres petits édifices, qui se trouvent au fond du cratère, ils appartiennent à deux types: des puys basaltiques d'une part, un puy doréitique d'autre part. Le plus remarquable des puys basaltiques est le Moussosomi, cône parfait haut de 75 m, agrémenté d'une courte coulée et qui est formé de basalte à olivine et augite. Le puy doréïtique, situé au SW, est plus irrégulier et dominé par une aiguille d'une dizaine de mètres; la roche qui le constitue est très comparable à celle du Toussidé.

Du point de vue génétique, il semble que le Trou au

natron se soit réalisé en deux ou peut-être trois explosions phréatiques successives. En effet, les dépôts de diatomites sur le replat de l'Ouest indiquent qu'il y avait avant la dernière, et la plus puissante explosion, un premier cratère dont le fond se situait vers 1.800 m, tandis que le fond actuel se trouve vers 1.450 m (l'altitude du plateau étant environ de 2.150 m du côté SE). Un redan distinct, au NW, pourrait correspondre éventuellement à une autre explosion.

6. - Le Doon Kidimi.

Trois kilomètres au NE du Doon, le Doon Kidimi est un cratère d'explosion qui mesure 1.500 m de diamètre extérieur et 1.200 m à la base. Il a 300 m de profondeur et ses parois sont plus verticales encore que celles du Doon, sauf suivant une étroite brèche qui permet dans l'Ouest une difficile descente. Les coulées que l'on observe dans les parois sont du même type que celles du Trou au natron, à l'exception de deux coulées plus sombres de trachyte à augite et, vers le haut, d'une coulée de basalte récent, tronquée aussi par l'explosion et recouverte par les cinérites.

Les bords du cratère sont recouverts par une brèche à éléments de roches claires et d'obsidiennes provenant de l'explosion. Le fond du cratère est plat, avec des alluvions fines, mais ne montre pas de dépôt lacustre.

Ici, l'explosion phréatique s'est réalisée en une seule fois, postérieurement à celles du Trou au natron car aucun bloc de rhombenporphyr n'est venu dans le Doon Kidimi, alors qu'ils sont normalement abondants dans tous les environs du Doon.

7. - Le Toussidé.

Centré sur le rebord Ouest de la caldeira du Pré-Toussidé et culminant à 3.265 m, le volcan du Toussidé domine le plateau d'environ 1.000 mètres. C'est un cône dont la base a 8 à 9 km de diamètres et dont les pentes sont fortes et atteignent 45° dans les 200 derniers mètres.

Les coulées qui en sont issues s'étendent sur plus de 200 km^2, d'une part à l'Est dans la caldeira du Pré-Toussidé et d'autre part à l'Ouest où elles atteignent les grès à 25 km du sommet. Toutes présentent un aspect très frais et se montrent grossièrement cordées. Elles sont constituées par des laves noires à faciès variable soit vitreux et compact, soit finement bulleux, soit scoriacé, soit surtout porphyrique à phénocristaux losangiques.

Le cône terminal est formé de produits pyroclastiques, lapilli et scories, qui ressortent en clair sur les coulées. A partir de la cote 3.000 apparaissent des fumerolles dont la température varie de 40 à 60 degrés.

Tous ces caractères ajoutés au fait que les coulées recouvrent toutes les autres laves, prouvent l'extrême jeunesse de ce volcan dont l'activité n'a cessé que depuis peu.

Du point de vue pétrographique, les laves du Toussidé sont principalement des trachytes sub-alcalins passant à des trachy-andésites dont la composition moyenne correspond à une doréïte de paramètres I (II), (4) 5, 3, (3) 4. L'étude microscopique montre, sur un fond vitreux avec quelques microlites indéterminables, des phénocristaux de sanidine finement maclée, des plagioclases, de l'olivine (fayalite) et de l'augite verdâtre.

8. - Le Timi.

Quinze kilomètres au Nord du Trou au natron et 5 km au NE de la caldeira du Pré-Toussidé, le volcan du Timi est un cône large de 7 à 8 km et dont le sommet atteint 3.040 m. On y trouve un cratère de 500 m de diamètre environ.

Il semble que le corps du volcan soit constitué par des trachytes sub-alcalins à augite et hypersthène, mais des coulées plus récentes en recouvrent la majeure partie. Ce sont des roches gris-noir à phénocristaux de feldspaths chatoyants et de section rectangulaire, dont la composition correspond à des trachy-andésites. Les éléments ferro-magnésiens caractéristiques sont une augite verdâtre, de la fayalite et des mi-

nerais noirs; l'hypersthène est présent dans certains échantillons.

Ces laves récentes sont en réalité très analogues aux doréites du Toussidé et leur fraîcheur permet de penser que les émissions des deux volcans sont contemporaines.

9. - Le Tarso Tôh.

Plus que dans les petits puys dispersés sur le Tarso Toussidé, les formations basaltiques récentes prennent une grande importance vers le NW, en constituant le Tarso Tôh, unité volcanique allongée sur 80 km d'Est en Ouest, avec une largeur de 20 à 30 km.

On y trouve de grandes coulées issues de nombreux puys bien conservés, dont l'allure générale rappelle ceux du Tibesti oriental et des environs du Mousgou. Ils reposent indifféremment sur le substratum antévolcanique (schistes antécambriens à l'Est, grès primaires à l'Ouest) ou sur des roches de la série blanche. On peut observer que la plupart sont recouverts par des cinérites provenant du Trou au natron; cependant il est possible que quelques puys et coulées soient plus récents que les explosions et qu'il convienne alors de les considérer comme équivalents à ceux du fond du Trou.

Du point de vue pétrographique, il semble qu'il s'agisse essentiellement de basaltes labradoriques à olivine et augite. A. Lacroix a néanmoins déterminé des andésites parmi les échantillons rapportés par la mission Dalloni.

IV. - Conclusions générales

A) Succession des phases volcaniques et leur âge probable.

Dans sa reconnaissance volcanologique du Tibesti, Dalloni avait distingué une série noire inférieure (basalto-andésitique), une série blanche moyenne (rhyolitique et trachytique), enfin une série noire supérieure (basaltique), toutes étant probablement, selon lui, d'âge quaternaire.

D'après nos observations, le schéma général de la succes-

sion des formations volcaniques reste valable, bien que de nombreuses retouches de détail soient devenues nécessaires.

La série noire inférieure n'a pas été observée partout. Mieux qu'ailleurs, elle semble représentée dans le Tibesti central et nord-oriental, mais nulle part nous n'avons reconnu d'appareil qui puisse être mis en rapport certain avec elle; aussi, son origine fissurale paraît-elle des plus probables.

La série blanche constitue l'essentiel de tous les grands édifices étudiés. Très homogène et puissante dans l'Ouest (Pré-Toussidé) et l'Est (Koussi), elle comporte par contre des niveaux noirs intercalaires dans le centre (Tarso Voon, Tarso Toon, Tarso Yéga) et le Nord-Est (Ehi Chi). Les caractères de cette série noire intermédiaire sont les mêmes que ceux de la série noire inférieure. On peut donc considérer que les émissions de la série blanche inférieure (laves et ignimbrites trachytiques dominantes) se seraient produites avant la fin des épanchements basalto-andésitiques inférieurs. Le volcanisme rhyolitique (intrusions, coulées et ignimbrites) serait par contre toujours postérieur et constituerait ainsi une série blanche supérieure.

La série noire supérieure doit être subdivisée, en fonction des dispositions topographiques qui prouvent des phases successives, en basaltes des plateaux, basaltes des pentes et des vallées anciennes, basaltes des vallées récentes. Pour la phase des plateaux, certaines confusions demeurent possibles avec la série noire intermédiaire, lorsque manquent les intrusions, coulées ou tufs rhyolitiques. Pour les petits puys basaltiques jalonnant le bord des grandes caldeiras ou disséminés sur les plateaux et les pentes, il est également quelquefois difficile de garantir l'attribution à l'une ou l'autre des phases. Le raisonnement basé sur la conservation de leur forme ou le degré d'altération de leurs produits demeure assez subjectif. Enfin, toutes les laves noires rattachées à la série supérieure ne sont pas nécessairement des basaltes. Rappelons les cas du Toussidé et du Timi, volcans subactuels, où ont été observés pantellérites, dacitoïdes, latites et surtout doréïtes, donc des roches qui, malgré leur faciès sombre,

appartiennent en réalité aux mêmes groupes que les rhyolites ou les trachytes.

En ce qui concerne l'âge des éruptions, nous ne pouvons pas conserver l'idée de Dalloni. Le Toussidé, les puys de surface des Tarsos, les coulées des vallées et une partie de celles des pentes, la plupart des caldeiras semblent appartenir seuls à un volcanisme quaternaire; par contre, la masse des basaltes inférieurs, des trachytes et rhyolites et certains basaltes des plateaux sont franchement indépendants des réseaux hydrographiques actuels et largement suspendus à des hauteurs dépassant parfois le millier de mètres.

Les terrasses ou niveaux lacustres interstratifiés dans ces coulées volcaniques anciennes n'ont fourni, jusqu'à maintenant, aucun fossile significatif permettant de les dater avec quelque certitude. Les arguments indirects auxquels il paraît logique de faire alors appel sont les suivants:

a) Les terrains les plus récents du substratum antévolcanique sont constitués par les grès de Nubie (sens strict). Le Lutétien de Libye reposant à l'extrême Nord du Tibesti sur les grès de Nubie faillés, sans être affecté lui-même par les failles, la tectonique est donc post-crétacée et anté-lutétienne. Le volcanisme fissural de la série noire inférieure pourrait avoir débuté à l'occasion du jeu, ou du rejeu, des grandes failles caractérisant cette tectonique, donc pendant le Crétacé terminal et l'Eocène inférieur, ainsi que le fait est prouvé dans d'autres régions du socle africain (Cameroun, Angola, Afrique orientale, Abyssinie, Yémen).

b) La phase d'érosion majeure, qui a modelé les grands traits du relief actuel et qui est postérieure aux séries noire inférieure et blanche moyenne, ainsi qu'aux basaltes des plateaux, est également postérieure au « Continental terminal ». Elle doit correspondre sensiblement à la limite entre Tertiaire et Quaternaire.

Grâce à ces coupures majeures et grâce aux phases d'érosion secondaires que nous avons reconnues, nous pouvons proposer, à titre d'hypothèse vraisemblable, la succession des phénomènes suivante:

Paléogène ? - Série noire inférieure, basalto-andésitique, d'origine probablement fissurale: Tarsos Abeki, Tamertiou, Oudingueur, Enneris Yeski, Yebbigué (Toon), Lellebi (Yéga), Tarsos Ourari et Tieroko, versant Nord-Ouest de l'Ehi Chi.

Miocène inférieur ? - Série blanche inférieure, esssentiellement trachytique, avec trachy-andésites, trachy-phonolites et quelques rhyolites, intrusions, éruptions et émission des ignimbrites anciennes: Pré-Toussidé, Sosso, Timi, Tamertiou, Abeki, Botoum, Voon, Toon, Yéga, Ourari, Ehi Chi, Kozen, Koussi; ponces, lapilli et diatomites d'Ouanofou et de l'Enneri Mousgou (Voon).

Miocène moyen ? - Série noire intermédiaire, basalto-andésitique: Voon, Toon, Yéga, Ehi Chi et Tchohonato.

Miocène supérieur ? - Série blanche supérieure, essentiellement rhyolitique, avec quelques trachytes et phonolites, intrusions, coulées et émission principale des ignimbrites: Pré-Toussidé et volcans voisins, Voon, Toon, Yéga, Ourari, Gozyidi, Chididemi, Aozi, Kegueur Tedi, Ehi Chi, en liaison avec l'affaissement majeur des caldeiras du T. Yéga, du Toon et peut-être partiellement des autres.

Pliocène ? - Série noire supérieure (première phase), du basalte des plateaux avec quelques andésites: Abeki, Tamertiou, Ourari, Ehi Chi, Godoon, peut-être Yéga et Toon ainsi qu'une partie des pentes du Koussi.

Quaternaire ancien ? - Affaissement majeur des caldeiras du Pré-Toussidé, du Voon et du Koussi externe, suivi par les éruptions basaltiques des puys et les coulées des pentes et vallées anciennes autour de ces caldeiras; soulèvement de Soborom; coulées des vallées anciennes de l'Ourari et du Yébbigué.

Quaternaire moyen ? - Puys basaltiques de la surface du Tarso Toussidé et des Tarsos du Nord-Est (Tuchussou); suite des grandes coulées des pentes et des vallées anciennes du Tôh (E de Wour), du Mohi, de l'extérieur du Koussi; affaissement de la caldeira interne du Koussi suivi par l'éruption des puys basaltiques qui la jalonnent.

Quaternaire assez récent. - Explosions du Trou au natron

et du Petit Trou du Toussidé, de l'Era Kohor et des autres Trous du Koussi; projection des cinérites à blocs autour de ces cratères d'explosion; ignimbrites récentes du Tibesti occidental, central et oriental.

Quaternaire très récent. - Eruption du Toussidé proprement dit et des puys du fond du Trou au natron; dépôt de diatomites et de trona du Toussidé et du Koussi.

Période actuelle. - Fumerolles du Toussidé ($\leq$ 60°); fumerolles, volcans de boue et sources thermales de Soborom ($\leq$ 100°); source thermale de Yi Yerra (38°).

B) Relation entre le volcanisme et la tectonique du Tibesti.

La tectonique postérieure aux grès du Nubie, qui affecte tout le substratum antévolcanique du Tibesti, est essentiellement une tectonique cassante dans laquelle on relève deux directions principales de failles.

Le premier réseau de failles, le plus développé, affecte l'Ouest, le centre, et le Nord du Tibesti. De direction SSW-NNE, il détermine, de Kourizo dans le NW au Miski dans le SE, une série de horsts et de grabens dont les plus remarquables sont le horst du Daski au Sud de Zouar, et les horsts du Dohozano et du bas-Yebbigué séparés par le graben du Guézendou au NE du massif.

Le deuxième réseau de failles, important surtout au Sud-Est et à l'Est du Tibesti, est de direction NNW-SSE au Sud du massif pour devenir NW-SE au Nord. L'accident le plus important dû à ces failles est le horst qui supporte le Tibesti sud-oriental (Emi Koussi et Tarso Ahon) et dans le prolongement duquel on observe au Sud-Est la série plissée d'Olochi.

Outre ces deux directions de failles qui, notons-le, correspondent aux directions tectoniques du socle antécambrien, il convient d'ajouter un axe privilégié, de direction NW-SE, bien marqué par l'alignement des falaises de l'Ager-Taï au Sud-Est et de l'Abo au Nord-Ouest. Cet axe correspond à un axe de bombement du socle qui ne paraît marqué par aucune faille.

Les relations entre le volcanisme et les accidents tecto-

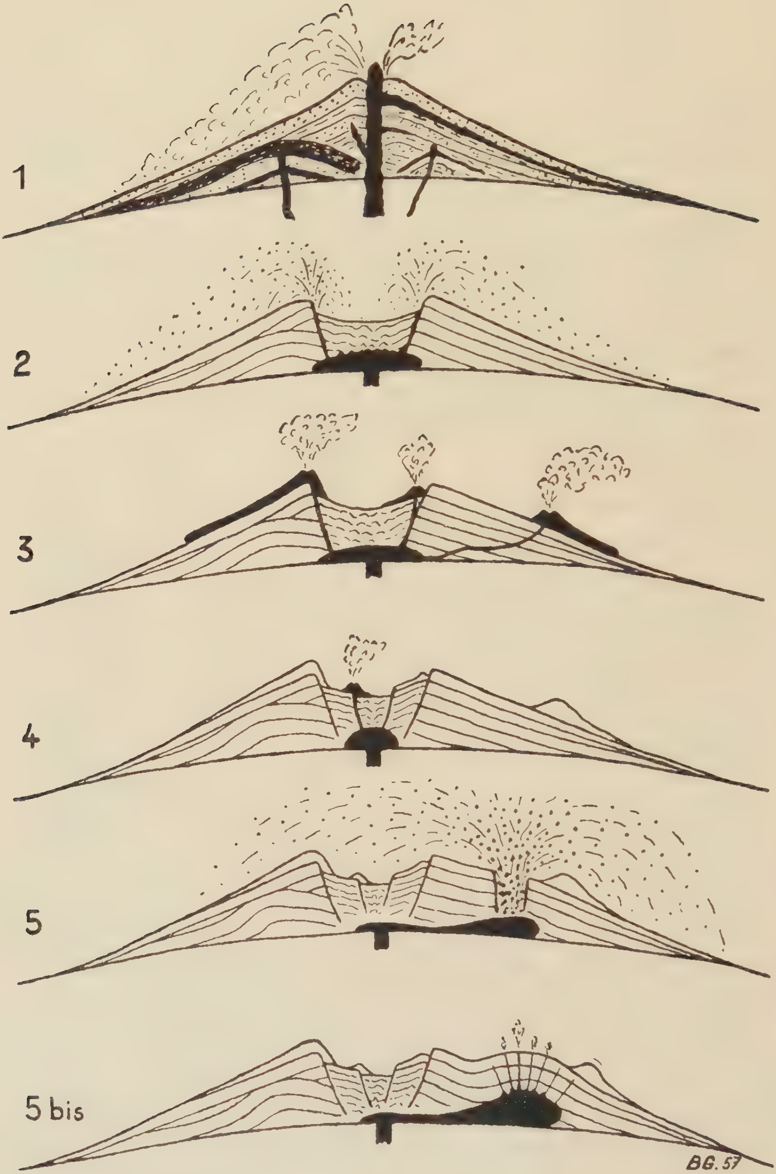

Fig. 4. - Schéma des principales phases de l'évolution des grands volcans du Tibesti.

1 = strato-volcan complexe de dynamisme strombolien et vulcanien (y compris le type péléen); 2 = caldeira d'affaissement, émission d'ignimbrites; 3 = cônes secondaires, jalonnant les contours de la caldeira ou adventifs; 4 = poursuite de l'affaissement, avec petits cônes secondaires; 5 = cratère d'explosion, émission de cinérites à blocs (type « Trou au Natron »); 5 bis = dôme volcano-tectonique, avec fumerolles (type « Soborom »).

niques apparaissent évidentes à la lecture de la carte géologique :

Dans le Tibesti sud-oriental, nous avons déjà dit que l'Emi Koussi et le Tarso Ahon reposent sur le substratum gauchi et relevé en horst par les failles NNW-SSE. En outre, si l'on prolonge au NW la faille limitant l'Ouest de ce horst, on rencontre successivement le Tarso Tiéroko, le Tarso Toon puis le Tarso Ourari. Dans l'alignement des failles bordant ce horst à l'Est on trouve les sorties de Chébédo puis des Tarsos Gozyidi, Kazena Lulli et Godoon. Enfin, dans la description du massif, nous avons noté également que l'alignement des puys basaltiques couvrant la dorsale du Tarso Ahon est parallèle au même réseau de failles.

Dans le Tibesti nord-oriental, on peut noter, outre les observations ci-dessus, que la bordure Est du massif correspond au prolongement du réseau de failles du Miski. Les sommets du Kégueur Tédi, du Mouskorbé, du Tarso Adar, du Tarso Chididemi et des aiguilles de Chébédo sont alignés suivant les mêmes directions.

La bordure Ouest du massif correspond au prolongement de la faille séparant le fossé du Guézendou du gradin surélevé du Dohozano.

Enfin nous avons noté dans la direction du massif que les filons de trachytes hyperalcalins de la série blanche inférieure et que les axes d'alignement des puys basaltiques récents étaient parallèles aux failles NW-SE affectant de part et d'autre du massif les grès primaires et les grès de Nubie.

Dans le Tibesti central, la limite SW est constituée par l'axe de bombement Ager-Taï - Abo qui passe d'ailleurs par le Tarso Abéki et est parallèle à l'alignement Tarso Yéga - Tarso Voon.

Le Tarso Yéga, l'Ehi Yeï et le Tarso Toon se trouvent dans le prolongement du réseau de failles SSW-NNE bordant l'Ouest du fossé du Guézendou, la structure de Kilébégué se trouvant, elle, dans l'axe de ce fossé.

Enfin nous avons noté plus haut que le Tarso Ourari, le

Tarso Toon et le Tarso Tiéroko se trouvaient dans le prolongement des failles bordières du gradin du Koussi.

Dans le Tibesti occidental, les Tarsos Abéki et Tamertiou, les massifs des Dadoï, du Botoum et de Sosso se trouvent dans le prolongement du Horst du Daski (au SW) et du fossé de Bardaï (au NE).

Le Toussidé, le Timi, la caldeira du Pré-Toussidé, le Trou au natron et le Doon Kidimi se trouvent dans le prolongement d'un deuxième horst, situé à l'Ouest de celui du Daski et plus bas que celui-ci.

La limite NE du massif est constitué par l'axe Ager-Tai, Abéki, Abo.

Enfin, l'allongement du massif basaltique du Tarso Tôh se trouve dans le prolongement d'une faille aberrante, sensiblement W-E, qui déplace les grès primaires à l'Ouest de Wour.

L'ensemble de ces observations montre que les relations entre la tectonique ayant affecté le substratum et le volcanisme sont étroites. En effet la plupart des édifices majeurs se trouvent sur des axes tectoniques importants et, en outre, se dressent sur des zones surélevées du substratum. On pourrait peut-être, pour expliquer cette dernière constatation, retenir une hypothèse analogue à celle formulée par P. Bordet pour le Hoggar: de vastes laccolites de roches éruptives, mis en place à profondeur moyenne à l'occasion de la phase tectonique intéressant les grès de Nubie, seraient causes des soulèvements; le volcanisme proprement dit aurait débuté peu de temps après dans les zones distendues de la couverture de ces laccolites.

C) Dynamisme des volcans du Tibesti.

Les conditions d'émission des séries noires anciennes nous sont mal connues; en effet, nous n'avons jamais observé nulle part d'émissaires conservés dans ces séries en dehors de quelques filons d'alimentation. Il est probable que les coulées qui les constituent sont pour la plupart d'origine fissurale. Cependant la présence fréquente de brèches et de niveaux

pyroclastiques importants à la base de ces séries montre que les émissions ont souvent débuté par un dynamisme de type strombolien ou même vulcanien, avec possibilité de nuées péléennes pendant le cycle basalto-andésitique intermédiaire (Tarso Yéga).

Les conditions d'émission des séries claires nous sont beaucoup mieux connues. Si les petits appareils isolés se présentent sous les formes les plus classiques (aiguilles, dômes, cumulo-volcans, etc.), par contre, les grands édifices complexes, liés surtout à l'émission de la série claire supérieure, sont tout à fait remarquables.

Leur genèse et leurs caractéristiques semblent liées à l'arrivée massive de magma à la surface de discontinuité entre substratum et formations volcaniques et à la plus ou moins grande facilité qu'a eu ce magma à s'insérer en laccolite sur cette surface ou à se frayer un chemin jusqu'à l'extérieur.

Dans un premier cas, le magma donne sans difficulté un large laccolite assez plat qui forme alors réservoir pour les extrusions et épanchements se produisant en surface. Ce réservoir se vide progressivement et il se crée une dépression qui provoque l'affaissement du cône sommital à l'intérieur de fractures jalonnant l'extension du laccolite. Pendant l'affaissement, celui-ci continue à se vider en émettant des nuées ardentes du type Katmaï qui utilisent les fractures périphériques pour parvenir à l'extérieur et sont à l'origine des masses considérables d'ignimbrites bien visibles tant à l'intérieur qu'à l'extérieur des caldeiras. On assiste alors à la formation des caldeiras du type Koussi, Yéga, Voon et Pré-Toussidé.

Dans un deuxième cas, le laccolite ne peut s'insérer que difficilement dans la surface de discontinuité; au lieu d'avoir une forme aplatie, il prend une forme bombée et soulève les formations antérieures. Ce soulèvement fracture la partie sommitale et permet l'accès en surface d'une grande quantité de laves à faciès extrusif. Le réservoir magmatique dans ces conditions est peu important et l'affaissement qui suit

son épuisement peu marqué, de même que sont moins développées les nuées ardentes de type Katmaï et, par voie de conséquence, moindre l'importance des formations d'ignim-

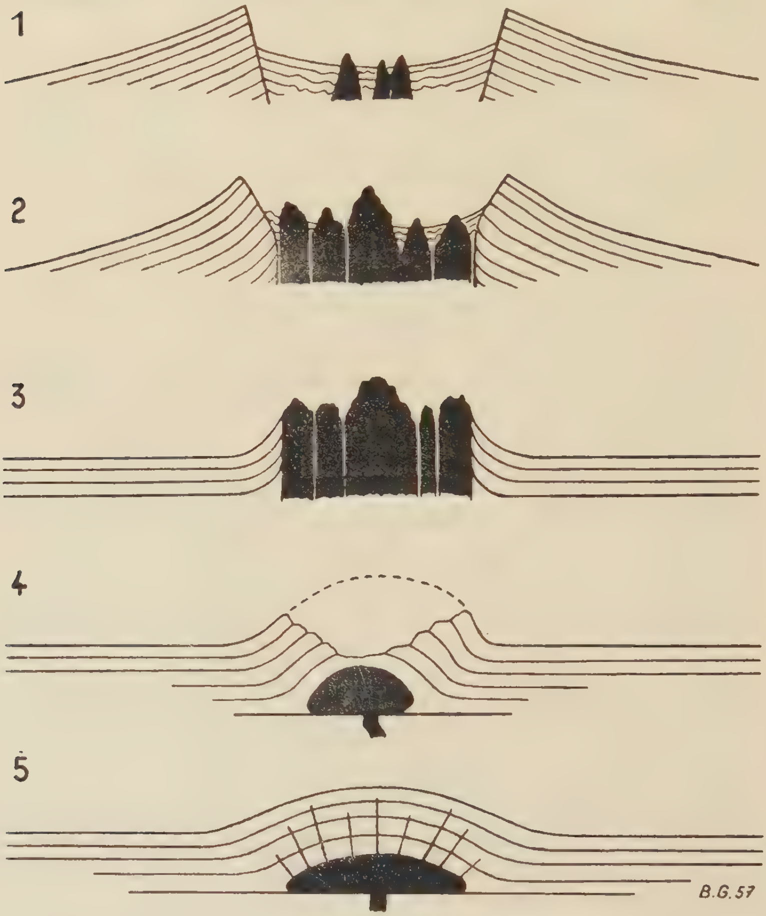

Fig. 5. - Schéma des types de caldeiras et de dômes volcano-tectoniques du Tibesti.
1 = caldeira d'affaissement; 2 = caldeira avec soulèvement compensateur; 3 = extrusion massive; 4 = structure annulaire (par érosion d'un dôme); 5 = dôme volcano-tectonique simple.

brites. C'est un schéma de ce type qui a dû présider à la genèse des massifs du Tiéroko, de Toon et de l'Abéki.

Dans un troisième cas (massifs du Tibesti nord-oriental, comme le Kégueur Tédi), le magma pénètre directement jusqu'à la surface en masses extrusives puissantes et ne forme pas de réservoir magmatique à mi-profondeur; il n'y a pas formation de caldeiras, et les émissions d'ignimbrites sont très limitées.

Des types un peu intermédiaires sont réalisés dans la structure radiaire de Kilébégué (extrusions « à bout de course », limitées à l'injection de fractures radiales, faible soulèvement au-dessus du laccolite probable, compensé par un effondrement réduit, sans genèse de caldeira), ainsi que dans les structures annulaires du Tarso Ourari (laccolites vraisemblablement de très petite taille, n'ayant guère entraîné qu'un soulèvement bien circonscrit).

Dans la plupart des grandes caldeiras d'effondrement (Koussi, Voon, Pré-Toussidé), les bordures déjà fracturées ont été le siège des émissions de basaltes supérieurs, avec formation de puys nombreux et de coulées parfois très longues (Koussi, Voon) ou de grands volcans doréïtiques (Toussidé, Timi). Mais l'affaissement a pu se poursuivre encore, avec genèse de caldeiras emboîtées (Koussi) et nouvelle phase de volcanisme basaltique.

Il est possible qu'en liaison avec ces derniers tassements un peu de magma non consolidé chassé latéralement, ou l'arrivée de nouveau magma au contact de la nappe d'eau présente dans le fond des caldeiras, ait motivé la genèse violente des cratères d'explosion du Koussi et du Tarso Toussidé. Dans un autre cas, l'introduction de ce magma s'est simplement traduite par la formation d'un petit dôme volcano-tectonique (Soborom).

En dehors des zones de caldeiras, l'émission de la série noire supérieure a surtout provoqué l'apparition d'une foule de petits cônes de scories et lapilli, plus ou moins stromboliens, en même temps que de larges épanchements de laves très fluides, à caractère presque hawaïen.

En définitive, le volcanisme du Tibesti présente certains caractères sans originalité spéciale, mais aussi d'autres qui

nous paraissent mériter de devenir classiques. Peu de régions au monde peuvent montrer un semblable groupement de caldeiras d'affaissement géantes, de grands cratères d'explosion, de soulèvements volcano-tectoniques indiscutables, ainsi qu'une aussi belle extension des ignimbrites.

Ajoutons que nous avons ici affaire à un volcanisme de « cratogène » continental typique où, suivant les théories en cours, les émissions devraient être essentiellement effusives et de caractère simique. Or les rhyolites abondent et les phénomènes explosifs n'ont pas manqué (nuées ardentes péléennes probables, de type Katmaï certaines, sans compter les cratères d'explosion) tous caractères que l'on considère comme liés au volcanisme d'« orogène », particulièrement dans les arcs insulaires. Il convient donc de nuancer les distinctions trop absolues proposées par divers auteurs.

1. - *Emi Koussi* (au dernier plan, au centre de la photographie) vu du Nord-Ouest à 60 km de distance. Au premier plan, grès primaires et secondaires; au second plan, témoins des coulées de rhyolites et trachytes du Tarso Ahon, dont le plus spectaculaire est le Teroane (à droite).

2. - *Emi Koussi*, versant N-W. Au dernier plan, témoins de coulées trachytiques sur les grès de Nubie. Au premier plan, coulées basaltiques des pentes et des vallées.

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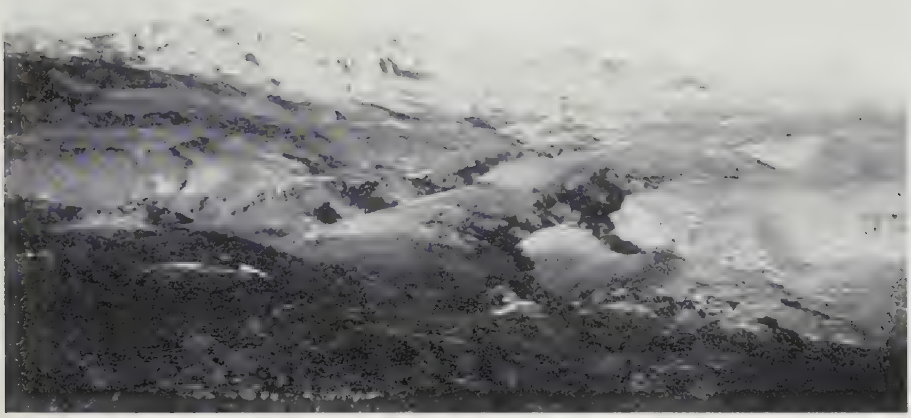

1. - *Emi Koussi,* versant N-E. Au dernier plan, rhyolites et trachytes du Tarso Ahon. Au premier plan, dominance de coulées basaltiques des pentes et des vallées.

2. - *Emi Koussi,* axe volcanique au N de la caldeira. Puys basaltiques récents (au fond) et subactuel (premier plan).

1. - *Emi Koussi.* Vue générale de la caldeira prise du N (Porte d
cinérites aux premier et second plans. Au dernier plan, au centre, à
sahariennes (3.415 m).

2. - *Emi Koussi.* Tiers NE de la caldeira. Trachytes, ignimbrites et c
Puys basaltiques récents et leurs coulées au second plan, à droi

Miski). Remparts trachytiques, puys basaltiques et
15 km de distance, le plus haut sommet des régions

nérites au premier plan, à gauche et au dernier plan.
e.

1. - *Emi Koussi.* Intérieur de la caldeira. Remparts trachytiques. Puy basaltique. Revêtement d'ignimbrites récentes et blocs rejetés par l'explosion de l'Era Kohor, au premier plan.

2. - *Emi Koussi.* Fond plan de la caldeira interne, jalonnée par des puys basaltiques à cratères égueulés. Au fond, les remparts trachytiques de la caldeira externe.

1. - *Emi Koussi.* Vue générale de l'Era Kohor (ou Trou au Natron du Koussi). Cratère d'explosion tranchant des formations essentiellement trachytiques. Dépôt blanc de natron (ou plutôt trona, carbonate de soude) dans le fond actuellement sec.

2. - *Emi Koussi.* Le champ de natron du fond du cratère d'explosion de l'Era Kohor. Falaises trachytiques hautes de 350 m. Liseré de basaltes récents au sommet.

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1. - *Tarso Yéga.* Vue générale de la caldeira, large de 20 km, en direction du N-W. Remparts essentiellement formés par la série noire, basalto-andésitique, intermédiaire.

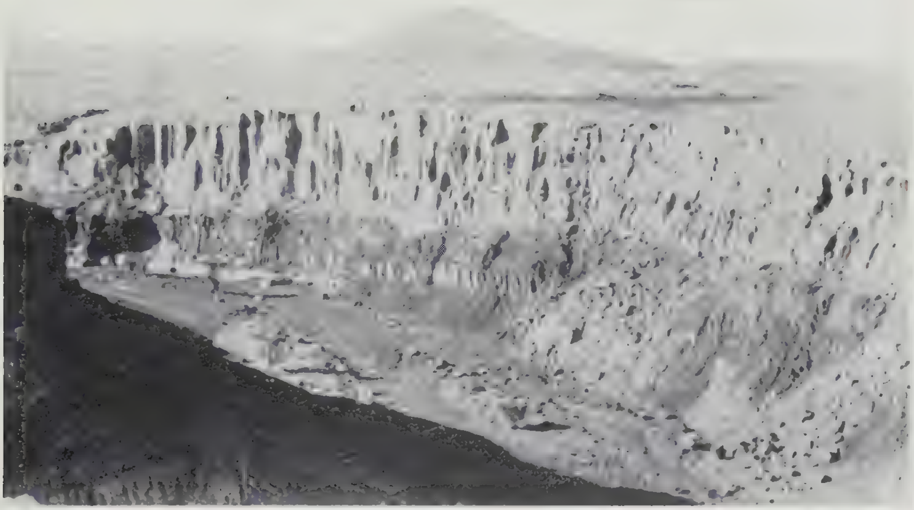
2. - *Tarso Tiéroko* (altitude: 2.910 m, au dernier plan), vu des pentes extérieures du Tarso Yéga, à 30 km de distance. Observer l'importance du relief du Tiéroko, où le soulèvement central a été probablement plus grand que l'affaissement générateur de sa caldeira.

1. - *Tarso Voon.* Vue générale de la caldeira, prise de son bord
18 km. Noter le plongement des coulées et ignimbrites rhyoli

2. - *Tarso Voon.* Vue générale de la caldeira, prise de son bord
plan, les remparts du Tarso Toon dominent la surface topog
(distance de 50 km).

1. - *Tarso Toon*, vu depuis le Tarso Voon. Noter les pentes fortes vers l'extérieur du volcan. La caldeira, d'un diamètre de 9 à 12 km, se développe entre les remparts dont on devine les limites.

2. - *Tarso Voon*. Le fond, aplani, de la caldeira, n'est troublé que par de rares sorties de la série blanche et des coulées appartenant à la série noire supérieure (premier plan).

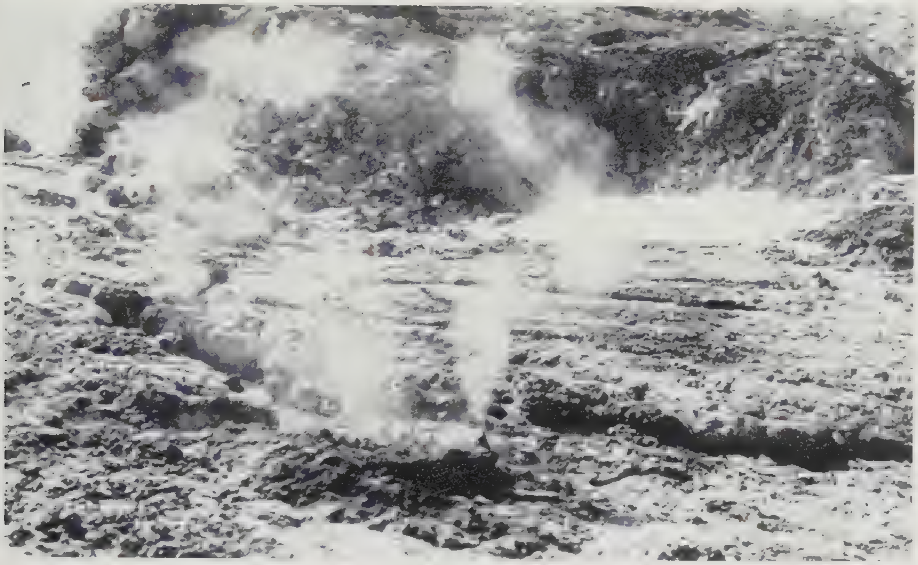


1. - *Ehi Mousgou* (3.100 m), au dernier plan, volcan formé de basaltes supérieurs recouvrant des sorties de la série blanche. Au premier plan, la coupe de l'Enneri Mousgou montre des ignimbrites rhyolitiques au-dessus d'une coulée basaltique prismée appartenant à la série noire intermédiaire, qui proviennent du Tarso Voon.

2. - *Enneri Mousgou.* Aspect caractéristique des ignimbrites supérieures (rhyolitiques) provenant du Tarso Voon.

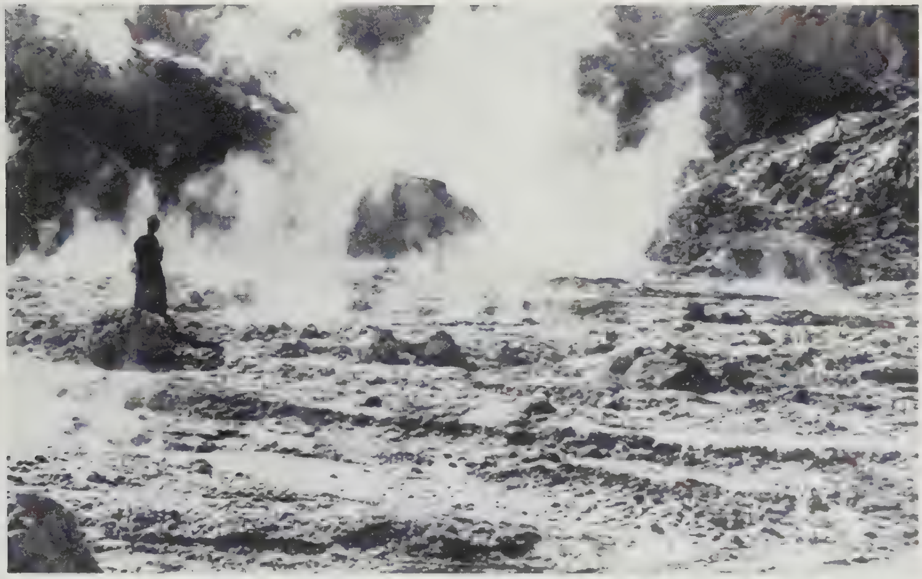
1. – *Soborom.* Vue générale de la partie orientale de l'aire solfatarienne.

2. – *Soborom.* Vue générale de l'aire solfatarienne en direction du Nord. On distingue la structure en dôme: série noire intermédiaire dans les premiers plans, falaises appartenant à la série blanche rhyolitique, sommets formés par les basaltes supérieurs au dernier plan.



1. - *Soborom.* Petit soufflard à 95-100° au premier plan; marmite d'eau à 56° au deuxième plan (groupe central).

2. - *Soborom.* Grande marmite à 70° de Soborom Kidissoubi, ou « Source tonnante » (groupe supérieur).



1. - *Soborom.* Groupe central des sources; zone de 65 à 82°.

2. - *Soborom.* Groupe oriental des sources; grande marmite à 62°, entourée de soufflards à 80 et 90°.

1. - *Toussidé.* Volcan récent, de 3.265 m d'altitude, vu du bord intérieur de la caldeira du Pré-Toussidé. Le cône terminal, formé de produits pyroclastiques, et où l'on trouve encore des fumerolles à 60°, domine de grandes coulées sombres de laves surtout doréitiques (distance de 10 km environ).

2. - *Toussidé.* Coulées récentes et puys adventifs vus du sommet, en direction de l'Ouest.

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1. - *Toussidé.* Grandes coulées doréitiques, dans le bas des pentes, vers 2.200 m d'altitude, à l'Est du cône terminal qui est visible au dernier plan.

2. - *Toussidé.* Chaos de laves doréitiques, vers 2.400 m d'altitude.

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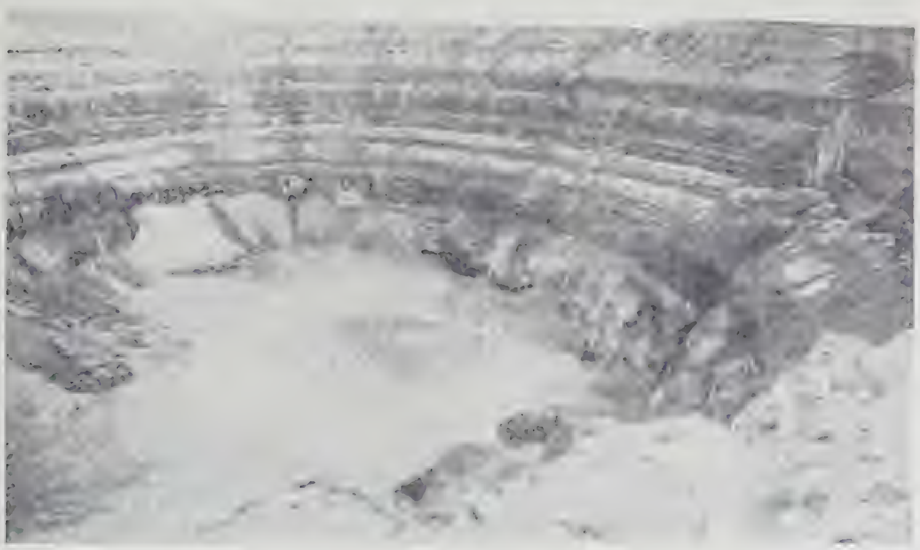
1. - *Trou au Natron.* Bord sud du cratère d'explosion. Au premier plan, blocs de trachytes, syénites (rhombenporphyr), etc., rejetés par l'explosion; au second plan, volcan basaltique récent mais antérieur à l'explosion et falaises de rhyolites et ignimbrites supérieures; au fond, le volcan très récent du Toussidé, en direction de l'Ouest.

2. - *Trou au Natron*, vu de son bord SE. A 8 km de distance la falaise la plus haute (1.000 m environ) correspond à la fois aux remparts de la caldeira du Pré-Toussidé et au bord du cratère d'explosion. Tranchant sur le dépôt blanc de carbonate de soude, dans le fond, se trouvent de petits puys basaltiques (le Moussossomi est le plus éloigné) et doréitique (le plus rapproché).

1. - *Doon Kidimi*, cratère d'explosion large de 1.500 m, tranchant les trachytes, rhyolites et ignimbrites du Tarso Toussidé, sur lequel s'observent les blocs rejetés par l'explosion.



2. - *Doon Kidimi.* Vue vers le fond, à 300 m au-dessous de la surface du Tarso. Coulées trachytiques et rhyolitiques, et ignimbrites antérieures à l'explosion.

FRANCESCO SIGNORE

(1886 - 1959)

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By A. Rittmann

Francesco Signore died at Naples, on November 29, 1959, in his seventy-third year. His death has caused a much lamented gap in the membership of the International Association of Volcanology.

Francesco Signore was born in 1886. After having obtained his doctorate in mathematics and physics, he began his academic career in 1914 as deputy assistant at the « Istituto di Fisica terrestre » at Naples. From 1915 to 1919 his scientific work was interrupted by the war, during which he served his country, first as observer in the aerostatic section, then as officer in the mountain artillery. He was decorated four times during the Balkan Campaign. He then returned to Naples, was promoted assistant in 1921 and collaborated with Prof. Chistoni, Prof. De Lorenzo and Prof. Scacchi. In 1922-1923 Prof. F. Signore took part in the precision levelling of the Phlegian Fields. At that time, the Prince Ginori-Conti, head of the famous establishment of Larderello, proposed that he investigates the possibilities of exploiting the volcanic vapours in that region. In 1924 Prof. F. Signore made a study of the seismological stations at Strasbourg, Brussels, Paris, and Zurich.

In 1927 he was named member of the Meteorological Section of the National Research Council and then of the Committee of Geodesy and Geophysics. In 1928 Prof. F. Signore was appointed assistant at the Vesuvius Observatory, where he was held in high esteem by the Director, Prof. A. Malladra, for his reliability and his efficiency in organizing and carrying out research.

From 1934 to 1956 he was Superintendent of the lectures on Volcanology in the Faculty of Science, Naples University, simultaneously, he taught physics and mathematics at high schools.

Prof. F. SIGNORE acted as General Secretary of the International Association of Volcanology with admirable devotion and efficiency from 1936 until his death. His profound wisdom, enthusiastic interest in Volcanology and Geophysics, his strong sense of responsibility and his charming personality and modesty earned him the highest regard of all volcanologists and the sincere friendship of many of them, who, like the writer were fortunate enough to collaborate with him more intimately and to profit from invaluable discussions with him.

We are sad to have lost such a colleague and friend and we shall remember him with deep gratitude, expressing our condolences to his wife and valuable collaborator Mrs. LIVIA LOLLINI - SIGNORE, M. D.

BIBLIOGRAPHY OF FRANCESCO SIGNORE

The publications of Prof. F. SIGNORE covered a wide range in geophysics. To this we should add a large number of reports concerning his activity in the International Association of Volcanology, International Union of Geodesy and Geophysics, and in the « Associazione Italiana di Idroclimatologia, Talassologia e Terapia Fisica », his editorship of the « Bulletin volcanologique internationale » and the final supervision of the printing of the « Catalogue of Active Volcanoes ». These are a better testimony than any words to the careful work of our late Secretary General.

(1) *Il temporale del 20 Giugno 1920*. Rend. R. Acc. Scienze Fisiche e Matem. di Napoli, Ser. III, Vol. XXVI, 1920.
(2) *Brevi notizie sulla nuova bocca della Solfatara di Pozzuoli*. Id., Vol. XXVII, 1921.
(3) *La pioggia torrenziale del 4 Novembre 1922*. Id., Vol. XXVIII, 1922.
(4) *Validità del coefficiente psicrometrico dello Sprung per il psicrometro a ventilatore elettrico, ecc*. Id., Vol. XXIX, 1923.

(5) *Il bradisisma in relazione coll'attività vulcanica nei Campi Flegrei.* Boll. Società Naturalisti in Napoli, Vol. XXXV (Serie II, Vol. XV), Anno XXXVII, 1923.
(6) *Sul fenomeno della mortalità del pesce nel lago Lucrino verificatosi nell'agosto 1922.* Rend. R. Acc. dei Lincei, Vol. XXXII, Ser. 5ª, Sem. 2°, Fasc. I, Roma, 1923.
(7) *Relazione su di una escursione fatta il 10 maggio 1923 nella plaga puteolana.* Boll. Soc. Nat. in Napoli, Vol. XXXVI (Serie II, Vol. XVI), Anno XXXVIII, 1924.
(8) *Pozzuoli.* Riv. Mens. di Cultura Moderna « Sirio », Anno I, n° 3, Salerno, 1924.
(9) *Sul metodo seguito per la determinazione delle temperature nei Campi Flegrei.* Boll. Soc. Nat. in Napoli, Vol. XXXVI (Ser. II, Vol. XVI), Anno XXXVIII, 1924.
(10) *Misure di temperature eseguite nel lago Lucrino e nei dintorni del « Maricello » durante il 1922-1923.* Rend. R. Acc. dei Lincei, Vol. XXXIII, Ser. V, I Sem., Fasc. 10°, Roma, 1924.
(11) *Valori orarî diurni delle precipitazioni registrate all'Istituto di Fisica terrestre della R. Università di Napoli (1917-1923).* Napoli, 1924.
(12) *Primo contributo allo studio geofisico del Cratere di Agnano.* Soc. Napol. per le Terme di Agnano, Napoli, 1924.
(13) *Contributo allo studio geofisico della Solfatara e del Rione delle Mofete-Stufe di Nerone.* Annali del R. Osservatorio Vesuviano, Terza Serie, Vol. I, Anno 1924.
(14) *La tettoia meteorologica modello « Circo Chistoni ».* Id.
(15) *Il Golfo di Napoli dal punto di vista della geofisica.* Atti del 1° Congresso regionale dell'Associazione Medica Italiana di Idrologia etc., Napoli, 1925.
(16) *Valori orarî diurni delle precipitazioni registrate durante il 1924 all'Istituto di Fisica Terrestre della R. Università di Napoli.* Annali del R. Osservatorio Vesuviano, 3ª Serie, Vol. I, Anno 1924.
(17 *L'Osservatorio Geofisico delle Terme di Agnano (I).* Rivista Mens. Illustrata « Le Terme di Agnano », Anno III, n° 1, Napoli, 1925.
(18) *La Geografia.* Rivista di Cultura « Sirio », Anno II, n° 4, Salerno, 1925.
(19) *L'Osservatorio Geofisico di Agnano (II).* Riv. Mens. Illustrata « Le Terme di Agnano », Anno III, n° 5, Napoli, 1925.
(20) *Valori orarî diurni delle precipitazioni registrate durante il 1925 all'Istituto di Fisica Terrestre,* etc. Annali del R. Osservatorio Vesuviano, Terza Serie, Vol. II, Napoli, 1925.
(21) *La probabile influenza della pioggia sull'attività della Solfatara di Pozzuoli.* Id., Id.
(21 bis) Questa nota è stata pubblicata anche in francese dalla Rivista « Ciel et Terre », Bulletin de la Societé Belge d'Astronomie, n° 5, Mai 1927, Année XLIII.

(22) *Gli Osservatorii Meteorologici nelle Stazioni Idroclimatiche e nei luoghi di cura.* Rivista delle Stazioni di Cura, Soggiorno e Turismo, n° 9, mese di Settembre 1926, Anno II, Roma, 1926.

(23) *Valori orari diurni delle precipitazioni registrate durante il 1926 all'Istituto di Fisica Terrestre,* ecc. Annali del R. Osservatorio Vesuviano, Terza Serie, Vol. III, Napoli, 1926.

(24) *Sguardo sintetico sui vulcani e sul clima della Campania.* Rivista dei Comuni di Cura, Turismo e Soggiorno, n.ri 1-2 Gennaio-Febbraio 1927, Roma, 1927.

(25) *Onoranze al Prof. Ciro Chistoni.* « La Meteorologia Pratica », Anno VIII, n° 2, 1927.

(26) *L'attività svolta dal Prof. Ciro Chistoni nell'Istituto di Fisica Terrestre della R. Università di Napoli.* Annali del R. Osservatorio Vesuviano, Terza Serie, Vol. III, Napoli, 1926.

(27) *Notizie Geofisiche su Napoli e dintorni.* Guida d'Italia del T.C.I. - Italia Meridionale II (Guida di Napoli e dintorni), Milano, 1927.

(28) *La radioattività delle acque termominerali di Lacco Ameno.* Atti del 18° Congresso di Idrologia, Climatologia e Terapia Fisica - Milano (3-6 ottobre 1927, V).

(29) *Il Clima di Agnano-Terme nell'anno 1926.* Atti del del 18° Congresso di Idrologia, Climatologia e Terapia Fisica - Milano 3-6 ottobre 1927, V).

(30) *Ciro Chistoni.* Bollettino del Comune di Napoli, Anno 53, n° 9, Settembre 1927 (V).

(31) *In memoria di Ciro Chistoni.* Bollettino Bimensuale della Società Meteorologica Italiana, n.ri 10-12, ottobre-dicembre 1927.

(32) *Misure di conducibilità elettrica dell'atmosfera nei Campi Flegrei.* Atti del XIX Congresso Nazionale di Idrologia ecc. nei Campi Flegrei, 1928.

(33) *Misure di radioattività di alcune sorgenti termominerali dei Campi Flegrei.* Id.

(34) *Osservazioni Meteorologiche eseguite all'Osservatorio Geofisico di Agnano-Terme (Campi Flegrei).* Id.

(35) *Das Vesuv Observatorium* - XXXV Jahresbericht des Sonnblick Vereines für das Jahr 1928, Wien, 1929.

(36) *Primo contributo allo studio della conducibilità elettrica dell'atmosfera al Vesuvio.* Annali del R. Osservatorio Vesuviano, Serie IV, Vol. I per gli anni 1927-1928, Napoli 1932, pag. 131.

(36 bis) Questa nota è stata riportata in francese nel « Bulletin Volcanologique », Organe de la Section de Volcanologie de l'Union géodésique et géophysique internationale, n° 15 à 18, 1928.

(37) *Il Reale Osservatorio Vesuviano e la sua attività scientifica.* Rivista di Fisica, Matematica e Scienze Naturali, Vol. III (2ª Serie), Maggio-Giugno 1929.

(38) *Brevi notizie geofisiche sui Campi Flegrei.* Atti del XIX Congresso Nazionale di Idrologia ecc. nei Campi Flegrei, 10-15 giugno 1928.

(39) *Il Clima di Agnano-Terme nel 1930.* Società Napoletana per le Terme di Agnano (Napoli), 1931.

(40) *Il clima dell'Osservatorio Vesuviano negli anni 1927-28.* Annali del R. Osservatorio Vesuviano, Ser. IV, Vol. I, Napoli, 1932, pag. 233.

(41) *La pioggia raccolta al Vesuvio, nel quinquennio 1924-28.* Annali del R. Osservatorio Vesuviano, Ser. IV, Vol. I, Napoli, 1932, pag. 181.

(42) *Il clima di Agnano-Terme nel 1931.* Società Napoletana per le Terme di Agnano (Napoli), 1932.

(43) *Présentation de deux diagrammes sismiques obtenus à l'Observatoire Royal du Vésuve pendant l'éruption du Vésuve de Juin 1929.* Bulletin de la Section de Séismologie de l'Union Géodésique et Géophysique internationale, Série A, Travaux Scientifiques, Fasc. n° 7, pag. 61, e nel Bulletin Volcanologique de l'Association de Volcanologie dell'Union G. et G. Int., 6me Année, N. 19 à 22, 1929, Napoli 1933, pag. 45.

(43 bis) La stessa nota è pubblicata in italiano negli Annali del R. Osservatorio Vesuviano, Ser. IV, Vol. II, pag. 275.

(44) *Sulla variazione d'attività del pseudo-vulcanetto di fango (fangaia) della Solfatara di Pozzuoli (Napoli) in seguito al grande terremoto dell'Irpinia.* Annali del R. Osserv. Vesuv., Ser. IV, Vol. II, Napoli, 1934, pag. 223.

(44 bis) La stessa in francese nel « Bull. Volcanologique » N. 19 à 22, 1929, Napoli, 1933, pag. 49.

(45) *Conducibilità elettrica dell'aria e pulviscolo atmosferico al Vesuvio* (con una tavola litografata). Annali del R. Osservatorio Vesuviano, Ser. IV, Vol. II, Napoli, 1934, pag. 229.

(45 bis) La stessa in francese nel « Bull. Volcan. » N. 19 à 22, 1929, Napoli, 1933, pag. 75.

(46) *Bibliografia Italiana Vesuviana dal 1845 ad oggi.* Annali del R. Osservatorio Vesuviano, Ser. IV, Vol. II, Napoli, 1934, pag. 17.

(47) *Riassunto delle osservazioni meteorologiche eseguite nell'Osservatorio geofisico « Ciro Chistoni » di Agnano-Terme durante il 1932.* Società Napoletana per le Terme di Agnano, Napoli, 1933.

(48) *La pioggia raccolta al Vesuvio nel 1929-1930.* Annali del R. Osservatorio Vesuviano, Ser. IV, Vol. II, Napoli, 1934, pag. 141.

(49) *Il clima del R. Osservatorio Vesuviano negli anni 1929-30.* Annali del R. Osservatorio Vesuviano, Ser. IV, Vol. II, Napoli, 1934, pag. 163.

(50) *Allure des facteurs météorologiques à l'Observatoire Vésuvien pendant l'eruption terminale du 3 au 8 juin 1929.* Bulletin Volcanologique,, N^os^ 23 à 26, 1930, Napoli, 1934, pag. 3.

(51) *Cinq ans d'observations à la « Solfatara dell'Atrio del Cavallo ».* Bulletin Volcanologique, N^os^ 23 à 26, 1930, Napoli, 1934, pag. 17.

(52) *La période séismique vésuvienne des premiers jours de février 1933.* Bulletin Volcanologique, Nos 23 à 26, 1930, Napoli, 1934, pag. 27.

(53) *I piccoli corpuscoli elettrizati e le polveri nell'atmosfera del Vesuvio.* (Terzo contributo). Annali del R. Osservatorio Vesuviano, Ser. IV, Vol. III, per gli anni 1931-32-33, Napoli, 1934, pag. 17.

(54) *Le radiazioni penetranti e il coifficiente di ricombinazione dei piccoli corpuscoli elettrizzati al Vesuvio.* (Quarto Contributo). Annali dell'Osservatorio Vesuviano, Serie IV, Vol. III, per gli anni 1931-32-33, Napoli, 1935.

(55) *L'attività scientifica esplicata dall'Associazione Internazionale di Vulcanologia dalla sua fondazione ad oggi.* Boll. del Comit. Geod. e Geofis. del C.N.R. - Ser. II, Anno V, N. 2, Aprile 1935, XIII.

(56) *Attività vulcanica e bradisismo nei Campi Flegrei.* Ann. R. Osservatorio Vesuviano, Ser. IV, Vol. III, per gli anni 1931-32-33, Napoli, 1935.

(57) *Bulletin Volcanologique,* organe de l'Association de Volcanologie de l'Union Géodésique et Géophysique Internationale, Ser. II, Tomes 22 (1937-1959), Napoli.

(58) *Rapporto riassuntivo sull'attività vulcanica nel Golfo di Napoli durante il triennio 1933-36.* B. V., Sér. II, Tome I, 1937.

(59) *La deficienza gravimetrica nella zona di Boscoreale.* Bull. Volcan., Sér. II, Tome II, 1937.

(60) *Rapporto sull'attività del Bureau International de Volcanologie.* Bull. Volcan., Sér. II, Tome VI, 1940.

(61) *Emanuele Soler.* Bull. Volcan., Sér. II, Tome VI, 1940.

(62) *Procès verbaux de l'Assoc. de Volcanologie, Oslo, 17-18 Août, 1948.* Bull. Volcan., Sér. II, Tome VIII, 1949.

(63) *Notizie geofisiche sul Golfo di Napoli.* La « Clinica Termale », Roma, 1948.

(64) *Alessandro Malladra.* Bull. Volcan., Sér. II, Tome VIII, 1949.

(65) *Antonino Lo Surdo.* Bull. Volcan., Sér. II, Tome VIII, 1949.

(66) *Procès verbaux de l'Assoc. de Volcanologie, Bruxelles, 20 Août - 1 Septembre 1951.* Bull. Volcan., Sér. II, Tome XII, 1952.

(67) *Le ricerche vulcanologiche in Italia nel triennio 1948-1950.* Bull. Volcan., Sér. II, Tome XIV, 1953.

(68) *Procès verbaux de l'Assoc. de Volcanologie, Roma, 14-25 Septembre 1954.* Bull. Volcan., Sér. II, Tome XV, 1955.

(69) *Sopra alcune sorgenti termominerali dell'Isola d'Ischia.* (Non pubblicata).

(70) *Procès verbaux de l'Assoc. de Volcanologie, Toronto, 3-14 Septembre 1957.* Bull. Volcan., Sér. II, Tome XIX.

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